5\

AEDC-TMR-79-E62

C.1

MULTIPLE VENTURI AIRFLOW MEASUREMENT SYSTEM CERTIFICATION FOR PROPULSION DEVELOPMENT TEST CELL J-2

R. B. Runyan
ARO, Inc.

September 1979

Final Report for Period August 1972 through December 1974

Approved for Public Release - distribution unlimited

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 1979**	2. REPORT TYPE	3. DATES COVERED **00-08-1972 to 00-12-1974**
4. TITLE AND SUBTITLE **Multiple Venturi Airflow Measurement System Certification For Propulsion Development Test Cell J-2**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **ARO, Inc., AEDC Division,A Sverdrup Corporation Company,Arnold Air Force Station,TN,37389**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**54**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

NOTICES

APPROVAL STATEMENT

This report has been reviewed and approved.

Daniel W. Cheatham III

DANIEL W. CHEATHAM, III, 1st Lt, USAF
Test Director, ETF Division
Directorate of Test Operations

Approved for publication:

FOR THE COMMANDER

James D. Sanders

JAMES D. SANDERS, Colonel, USAF
Deputy for Operations

SUMMARY

The objectives of this study were to evaluate the J-2 airflow measuring systems. The study provides the results comparing flowrates for various configurations from six fixed and eight remote actuated venturis having a nominal throat diameter of 10.2 in. to two reference venturis of 35 in. and 13 in. throat diameters. Pressure ratios across the venturis from 1.15 to 2.85, and inlet temperatures of 520, 680 and 770°R were investigated.

CONTENTS

APPENDIXES

APPENDIXES
(Cont'd.)

Page

II. TABLES

NOMENCLATURE

SV	Reference Venturi
C	Coefficient
P	Pressure, Psia
RN	Reynolds Number
TT	Total Temperature, °F, °R
W	Weight Flow, lb/sec

Subscripts

AVG	Average
A1N	Multiple Venturi Area
F1	8 Ft. Duct Station
Max	Maximum
Min	Minimum
MV	Multiple Venturis
MVI	Multiple Venturis Inlet
S	Static
SA	Conical Screen Inlet
SV	Reference Venturi
T	Total
ØØ	Venturi Inlet Plenum
1	Venturi Downstream Plenum
1N	Venturi Inlet

I. INTRODUCTION

Airflow in the J-2 Test Cell is measured by means of a multiple venturi system. The system has provisions for installation of 49 venturis, each with a nominal throat area of 82.5 sq. in. and of a standard design as described in Reference 1. Eleven of these venturis are remotely controlled open or closed to maintain choked conditions. The remaining venturis are fixed but may be opened or closed pre-test by installing or removing blanking plates. Eleven fixed and six remote actuated venturis were used for this testing as described in subsequent paragraphs of this doc document.

The airflow measurement system for J-2 was certified by comparison of measured airflow at the venturi station with airflow measured by a reference venturi installed downstream. Pressure and temperature distortion were also measured up- and downstream of the venturi airflow measuring station. Leak checks were conducted to measure the leakage into the plenum downstream of the venturis.

The certification was to support testing conducted by AEDC under the sponsorship of the Aeronautical Systems Division (ASD), Air Force Systems Command (AFSC), Wright Patterson Air Force Base, Ohio under Program Element 64215F.

The results were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation), contract operator of the AEDC, Air Force Systems Command (AFSC), Arnold Air Force Station, TN. The tests were conducted in Propulsion Development Test Cell J-2 of the Engine Test Facility (ETF) thru February 1974 under ARO Project Numbers RA175, RA299 and RA351.

II. APPARATUS

A. J-2 Test Cell

J-2 Test Cell is water-cooled and is 20 ft in diameter by 69 ft long. Test articles are installed through a 180 deg. clam shell hatch which is 34 ft 4 in. in length and opens 30 deg beyond cell vertical. Air is supplied to the test article by rotating machinery through a 5 element control valve with core breakers to a plenum with a flow straightener of honeycomb and punched plate upstream of the venturi airflow measuring station. Airflow from the venturi station enters a plenum which supplies the test article with airflow through an 8 ft duct which has a conical inlet screen and perforated plate flow straightener installed. Airflow from the 8 ft duct normally enters the test article through a bellmouth installed in the 8 ft duct.

B. Test Setup

The airflow certification testing was accomplished with the use of a reference venturi installed at the downstream end of the 8 ft duct in place of the test article bellmouth. Figure 1 shows the test cell layout with the venturi installed. The airflow venturi measurement setup for the certification testing is shown in Figure 2. Venturis even numbered and with an "A" prefix are remotely controlled open or closed while all other venturis are fixed for testing and must be opened or closed prior to test by installation or removal of blanking plates. The Reference Venturi was installed in the 8 ft duct as shown in Figure 2. Two reference venturis were used, one with a 35 in. throat diameter and one with a 13 in. throat.

C. Instrumentation

Instrumentation used is summarized in the table shown on Figure 1. Details of measurement locations are shown in Figures 3 and 4.

D. Data Conditioning and Recording

The pressures, temperatures and venturi positions were recorded by a computer controlled digital data acquisition system (DDAS). The system operates at 20,000 samples per second. The scan rate for each channel was 100 samples per second. Pressures were measured using a scanner valve system which has the capability of scanning 720 channels of pressure measurements with 60 scanner valves. Scanner valve pressure channels are in-place calibrated while temperature channels are millivolt substitution calibrated.

Data obtained on the DDAS are recorded on magnetic tape and are either simultaneously transmitted to the data reduction computer for computation or are reduced at a later time from the magnetic tape.

On-line engineering units data display is provided by the DDAS on an alpha-numeric CRT display whose image is transmitted to the control room by closed circuit television.

III. PROCEDURE

Testing was accomplished at airflows ranging up to 300 lb/sec and the number of venturis controlled to produce venturi pressure ratios of 1.15 to 2.85. Steady state data was recorded by the DDAS for each set condition and airflow was calculated for the multiple venturis and the reference venturi. Inlet air temperatures of 520,680 and 770°R were set during one test to determine the temperature distortion and its effect on airflow measurement. A summary of the venturi configurations tested is found in Table I.

IV. RESULTS

A. Flow Coefficients

The venturi design used as a standard for the J-2 multiple venturi system is as described in Ref. 1.

A computer program was used to calculate the flow coefficient for the multiple venturis and reference venturi and was used to determine the effect of pressure, temperatures and Reynolds number. The computer program provided a theoretical means of determining flow coefficient as a function of pressure, temperature and Reynolds number. Figure 5 shows the comparison of the choked flow coefficient for the multiple venturis and the 13 and 35 in. reference venturis. It is evident that Reynolds number nondimensionalizes the choked coefficient to within ±0.025% for the variables of pressure, temperature and throat diameter. To account for the small differences shown the coefficient data for the 35 in. venturi was curve fit separately as shown in Figure 6. The equation is presented on the figure for the 35 in. venturi that relates CF to RN. The multiple venturi coefficient was surface fit as a function of temperature and pressure. Figure 7 shows this surface fit and the equation derived for it.

Only the multiple venturis were considered for unchoked flow conditions. The CF was evaluated for various temperatures, pressures, and pressure ratios. It was determined that the temperature effect was insignificant from Figure 8 where CF is plotted vs pressure ratio. The equation on Figure 8 is for the CF with pressure and pressure ratio as the variables. The pressure ratio used is the theoretical pressure (throat wall static pressure to inlet total pressure) calculated by varying the throat Mach number.

B. Pressure Distortion

Pressure distortion was determined by calculating (PMax–PMin)/PAvg at Station ØØ (multiple venturi inlet) and Sta. 1.0 (8 ft duct). The distortion at Sta ØØ is shown in Figure 9 as a function of venturi flow corrected to standard conditions at Sta ØØ. The distortion is generally below 1.0% and airflow level does not have a significant effect on distortion. This was as expected because of the low Mach (<0.03) number in the 20 ft dia. plenum. Therefore, the Sta ØØ distortion is primarily a result of the flow pattern from the facility valves upstream of the multiple venturis.

The distortion at Sta 1.0 in the 8 ft duct is shown in Fig. 10 as a function of corrected airflow. The maximum corrected airflow level for the B-1 test will be approximately 350 lb/sec. which would result in distortion levels less than 1%. The distortion approaches 3 percent at corrected airflow levels of 1200 lb/sec and duct Mach number of 0.3. The 8' duct Mach number as a function of airflow is shown in Fig. 11.

Distortion measurements are also influenced by pressure level as can be seen from Fig. 12. Pressure level effect was obtained by utilizing one venturi and varying the pressure level at Sat. ØØ and Sta. 1.0. The effect of flowrate is insignificant in comparison to the effect of pressure level. The effect shown here is primarily the result of excessive pressure measurement precision error at the low levels of pressure (<6 psia) with the pressure transducers used. This indicates that to obtain precise measurements below 5 psia extra care must be taken by setting pressure levels during systems calibration in the range of the data to be obtained.

C. Temperature Distortion Effects

The effect of inlet temperature variation on flow measurement was investigated by varying the inlet total temperature (TT 00) to the venturis. The increased temperature resulted in temperature distortion at the venturi inlet shown in Fig. 13 of 9 to 10 percent for inlet temperature approaching 800°R. There was some effect of the venturi pattern used as shown by the comparison of Group 1 to Group 2, but was a smaller effect than the effect of temperature increase on distortion. The effect of this resulting distortion on the airflow measurement can be seen by comparing the flow measured with the multiple venturis and the single downstream venturi. This comparison is presented in Fig. 14 with the multiple venturi flow up to 0.7 percent higher than the single venturi flow (WSV). This difference was primarily a result of the inadequate sampling with the temperature probes due to the temperature distortion at the inlet to the multiple venturis.

An attempt was made to account for the sampling error by determining temperature profiles from the measured data. The profiles were too complex to easily determine mathematically; therefore, engineering judgment was primarily used to establish profiles. Positions of equal area on the venturis in ring A and B were used to determine temperature from the established profiles. These equal area temperature values were then used to correct the upstream venturi flow on a few selected data points having high distortion levels. The resulting flow was then compared to WSV flow and is shown in Fig. 15. The improvement is significant and though some scatter remains in the data it is evident that the high temperature distortion resulted in a sampling error. To eliminate this sampling error a three-probe rake was placed across each of the outside venturis in Ring A.

D. Reference Venturi Flow Comparison

Verification of airflow measurement validity was determined in these tests by comparison of multiple venturi airflow calculations with airflow calculated for the reference venturi. Several configurations of multiple venturis were used. The effect of configuration on airflow measurement as shown on Figure 16 was determined to be insignificant in comparison to data scatter.

The comparison of multiple venturi airflow with reference venturi as a function of overall pressure ratio is shown in Figure 17. The flow through the reference venturi is choked at all test conditions. The choked flow calculation for the multiple venturis is valid to a pressure ratio as low as 1.25. Unchoked flow calculations must be used below a pressure ratio of 1.25. The average agreement of the multiple venturi with the reference venturi is 0.2% within the choked flow range and 0.45% with the multiple venturis unchoked.

An error analysis of the airflow measuring capabilities resulted in the following estimation of the airflow measurement uncertainty over the choked flow range.

At the 95 percent confidence level the possible bias of 0.24 percent and a precision of 0.21 percent combine to give a total airflow measurement uncertainty of ±0.45 percent.

E. Unchoked Flow

The calculation of flow when the venturi is unchoked requires the measurement of the throat static pressure. Figure 18 shows the theoretical inlet to throat static pressure ratio as a function of temperature for the multiple venturi design. Figure 19 shows the measured inlet to throat static pressure ratio at a constant temperature for each of the multiple venturis used. The measured inlet to throat static pressure ratios vary from the theoretical and also vary as a function of the overall pressure ratio below 1.4 even though the venturi is choked to a pressure ratio of 1.25 as shown on Figure 17. These variations in pressure ratio are a result of variations in as-built venturi geometry and throat static pressure tap installations not being in the minimum area plane.

The measured inlet to throat static pressure ratio is corrected by the amount of deviation from the theoretical pressure ratio before the venturi coefficient is calculated.

The corrected unchoked throat static pressure is calculated as follows:

PRACT	=	The measured choking pressure ratio (Inlet total to throat static)
PS1N	=	The measured throat static pressure
PRTH	=	The theoretical pressure ratio (Inlet total to throat static)
POO	=	The measured total inlet pressure
PRACTX	=	The corrected measured pressure ratio (Inlet total to throat static)
PS1NX	=	The corrected measured throat static
TOO	=	The measured inlet total temperature °R

$$PRTH = 0.477843 + .869 \times 10^{-5}\ (TOO - 500)$$

$$PRACTX = PRACT + 0.869 \times 10^{-5}\ (TOO - 500)$$

$$PS1NX = POO \left[1.0 + \left(\frac{PS1N}{POO} - 1\right) \left(\frac{PRTH - 1.0}{PRACTX - 1.0}\right)\right]$$

The value of PS1NX is used in correlation with Figure 8 to obtain the venturi coefficient. The unchoked flow is calculated at a pressure ratio across the multiple venturis of approximately 1.15 using the above correction and is shown as the solid symbols in Figure 17.

F. Leakage Flow

Figure 20 shows the results of inleakage airflow tests conducted to determine the rate of leakage as a function of inlet pressure at the reference venturi (P1). Inleakage flow is small (0.2 lb/sec) and is insignificant when compared to the airflow range of interest in B1 (F101) engine testing at 100 to 350 lb/sec.

IV.

SUMMARY OF RESULTS

The results of the venturi airflow certification are summarized as follows:

1. Pressure distortion at Station ØØ is less than 1% below 350 lb/sec airflow.

2. Pressure distortion at Station 1 is less than 1% below 350 lb/sec airflow.

3. Temperature distortion ranges from 2% at 520°R to 9% at 760°R at Sta. ØØ.

4. Changes in the temperature-sampling procedure reduced the effect of TT distortion on flow rate calculation from -0.7% to ±0.3%.

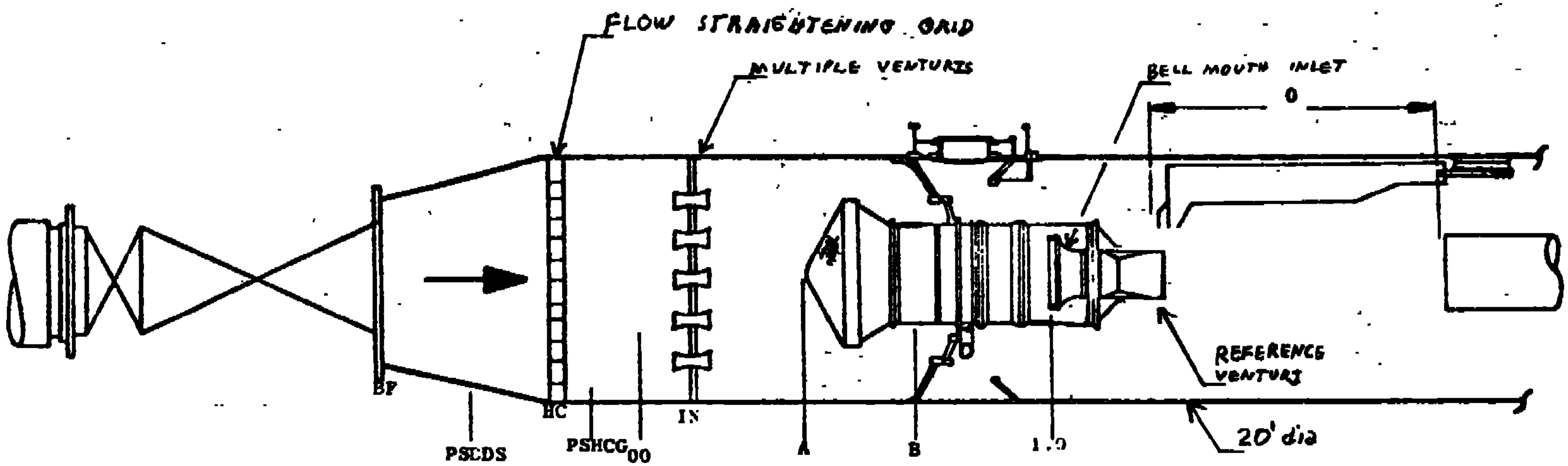
5. The effect of multiple venturi configuration on airflow measurement is insignificant.

6. Airflow calculated at the multiple venturi station compares with the reference venturi airflow calculation to within an average of 0.2% choked and 0.45% unchoked.

7. The airflow measurement uncertainty at the 95 percent confidence level was determined to be ±0.45 percent for venturi choked flow.

REFERENCES

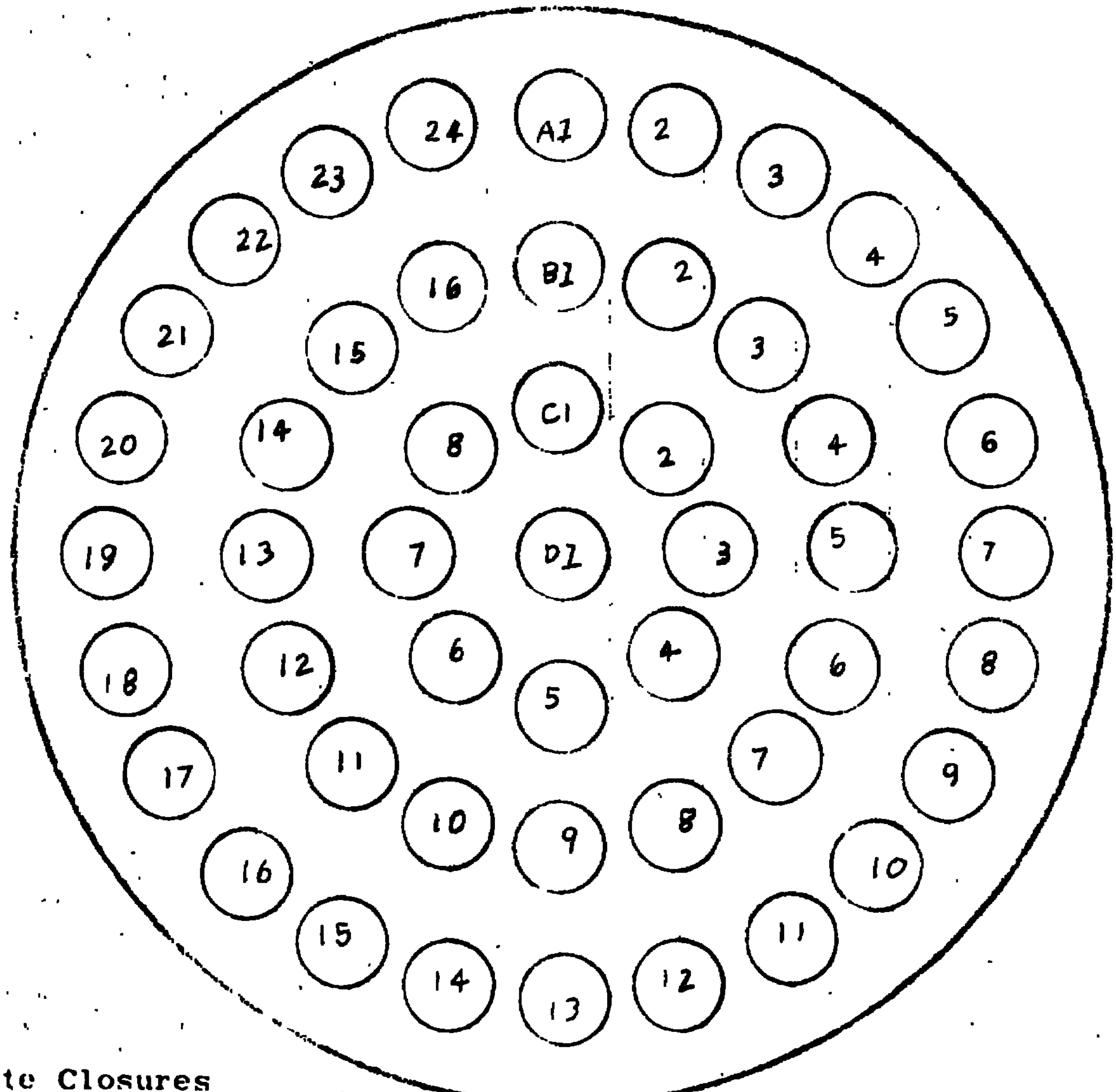
1. Robert E. Smith, Jr. and Roy J. Matz. "Verification of a Theoretical Method of Determining Discharge Coefficients for Venturis Operating at Critical Flow Conditions". AEDC-TR-61-8, September 1961.



Station Identification		Total Press.	Static Press.	Total Temp.	Skin Temp.	Strain Gages
BF	Valve baffles					
HC	Honeycomb		2			
00	Venturi inlet	48		20		
IN	Venturi throat		18		36*/18**	
A	Conical screen inlet		1			
B	Cylindrical screen inlet		1			
1.0	8 ft. duct rakes	20	4	20		
01	Bellmouth	24	24/16		2	

* Installed
** Hooked up

FIG. 1 J-2 Cell Layout

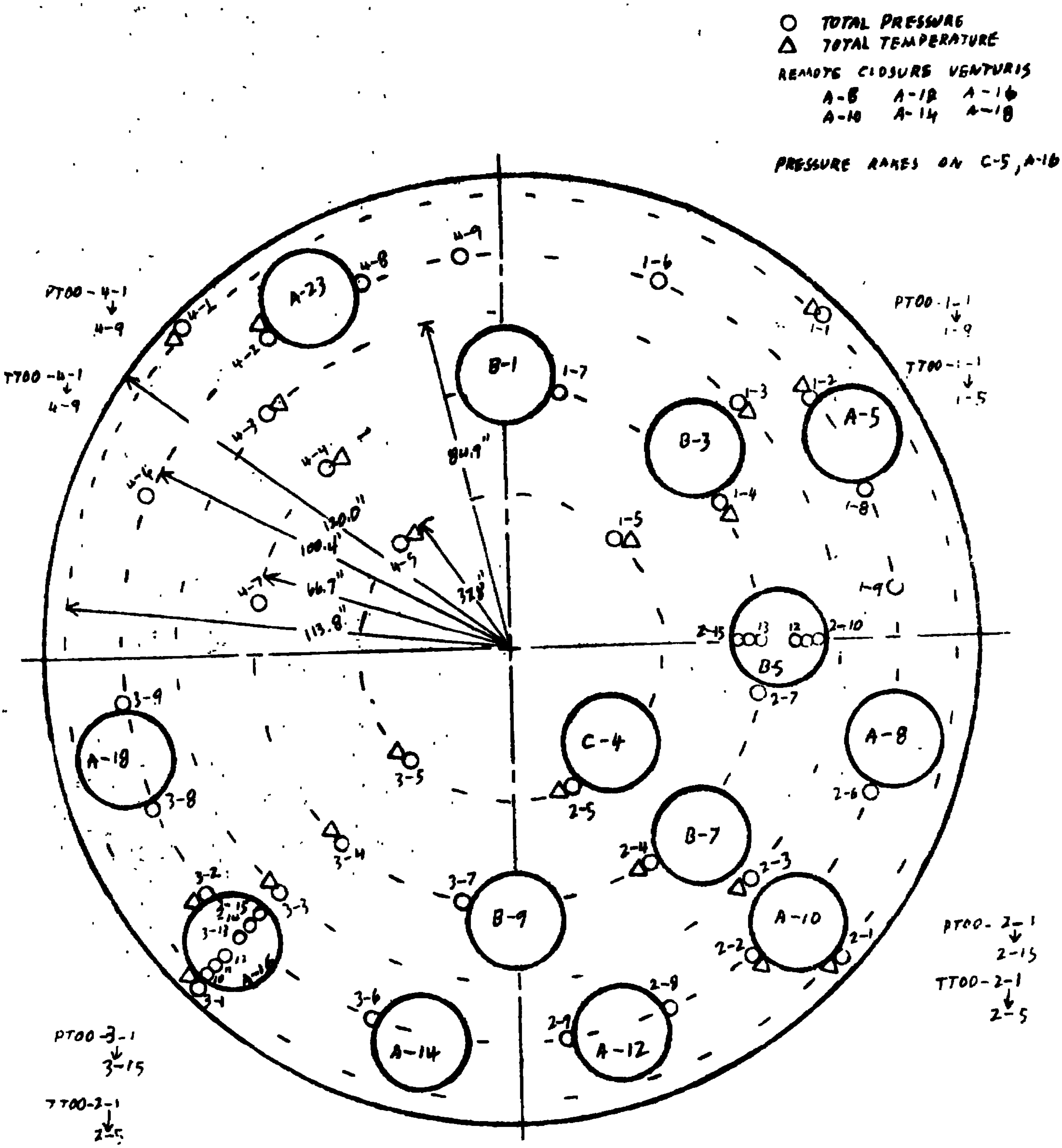


Remote Closures
(A) 2, 4, 6, 8, 10, 12, 14,
16, 18, 20, 22

Looking Upstream
Not to Scale

Multiple Venturi Meter Locations (Total Planned)

Figure 2



LOOKING UPSTREAM

J-2 VENTURI FLOW MEASURING SYSTEM INSTRUMENTATION AND VENTURI CONFIGURATION

Figure 2

(Cont'd)

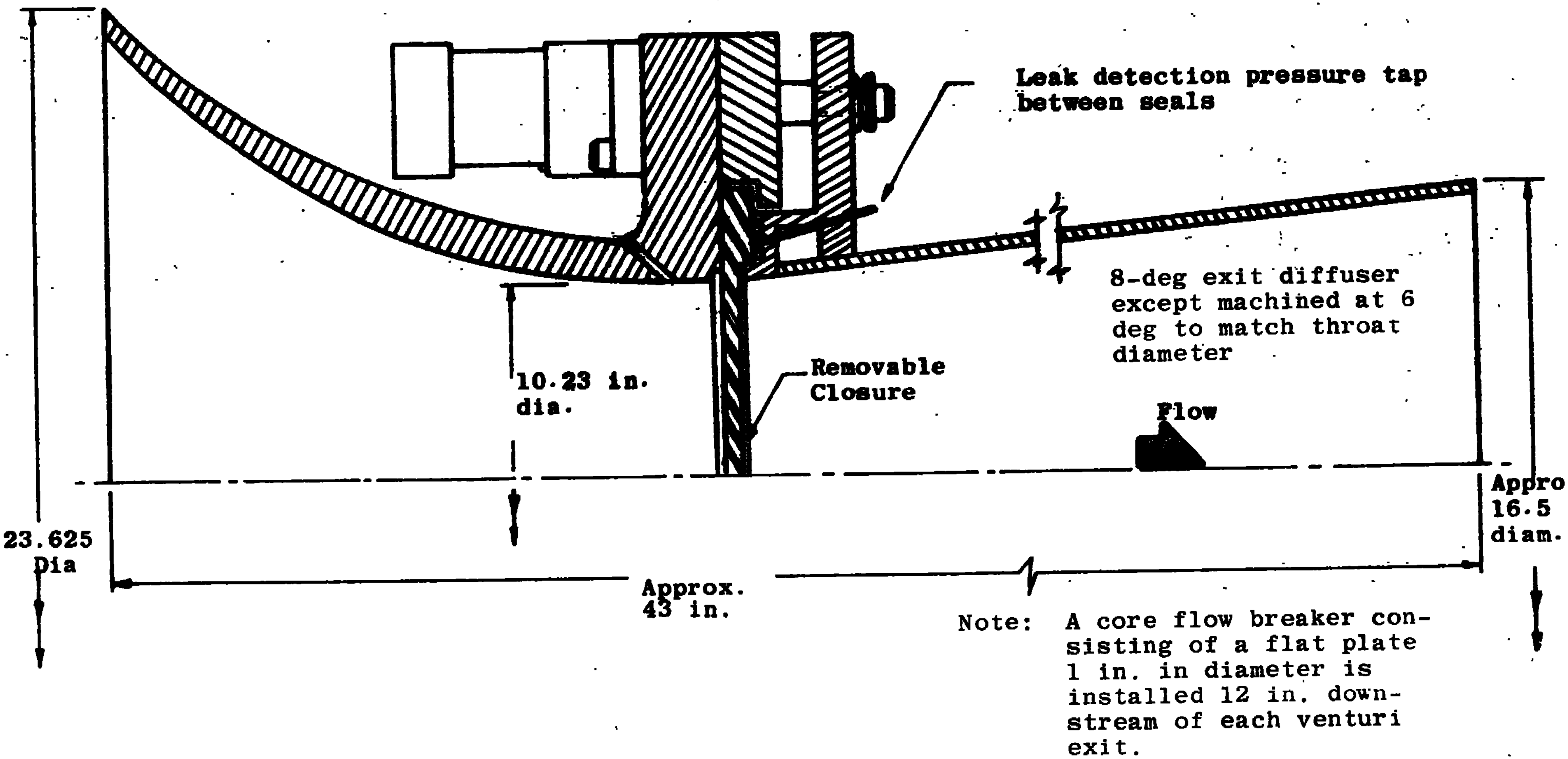
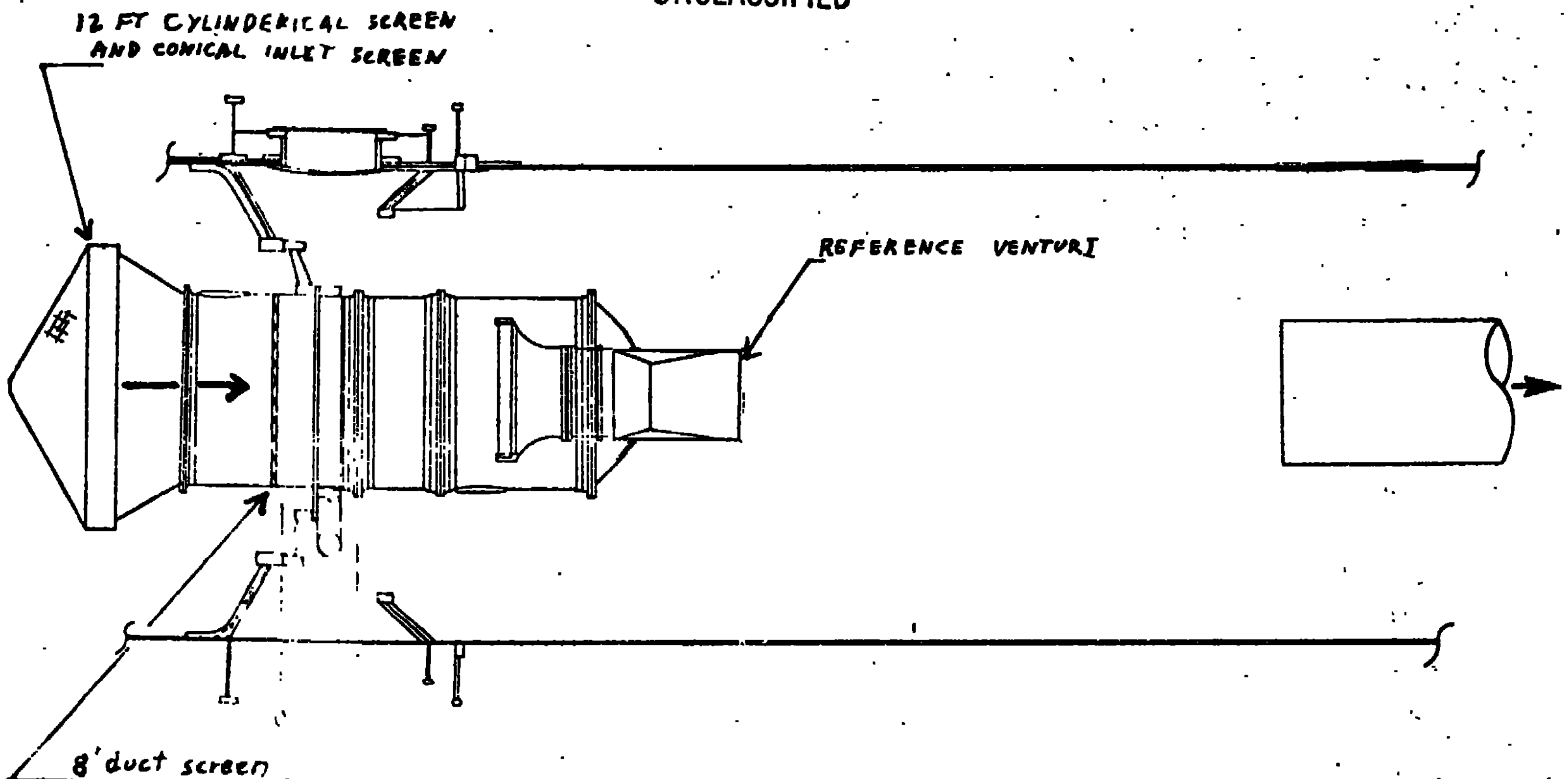
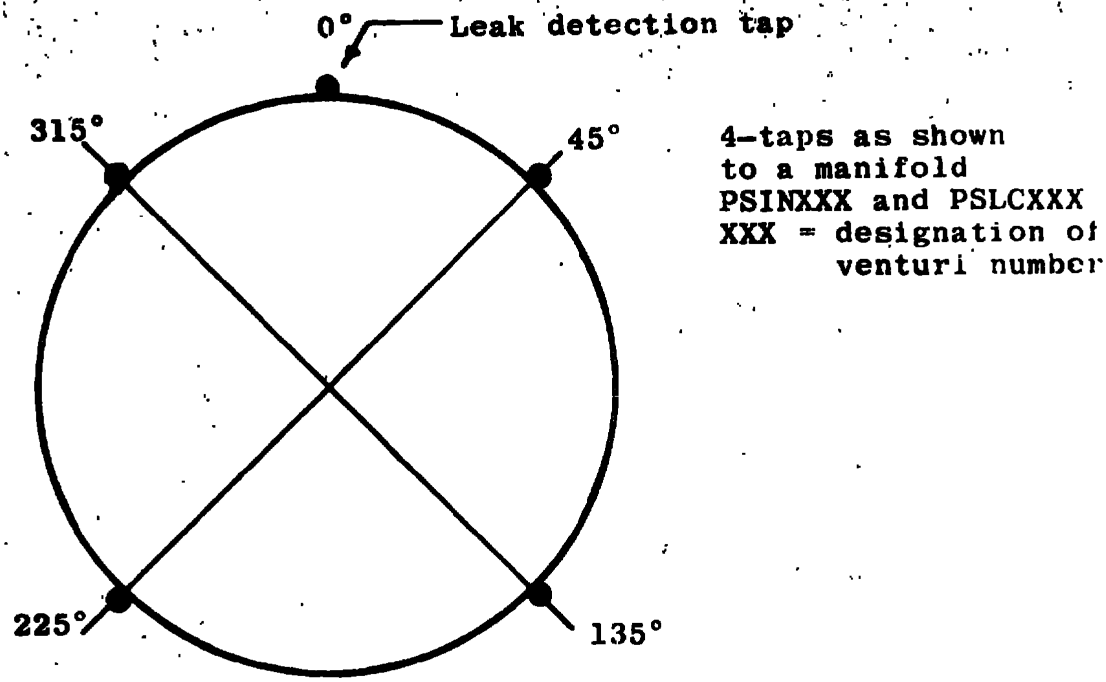


Figure 2
(Cont'd)

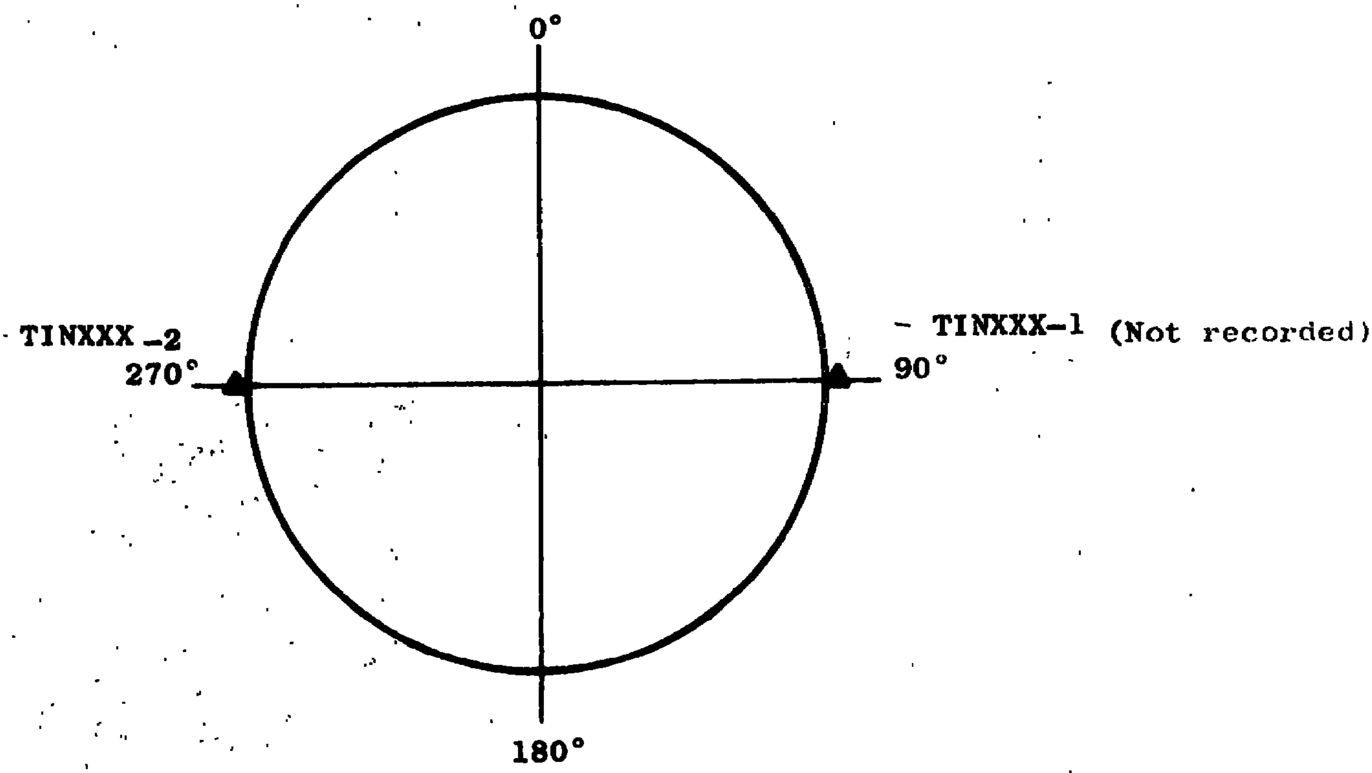


REFERENCE VENTURI INSTALLATION

Figure 2 CONCLUDED



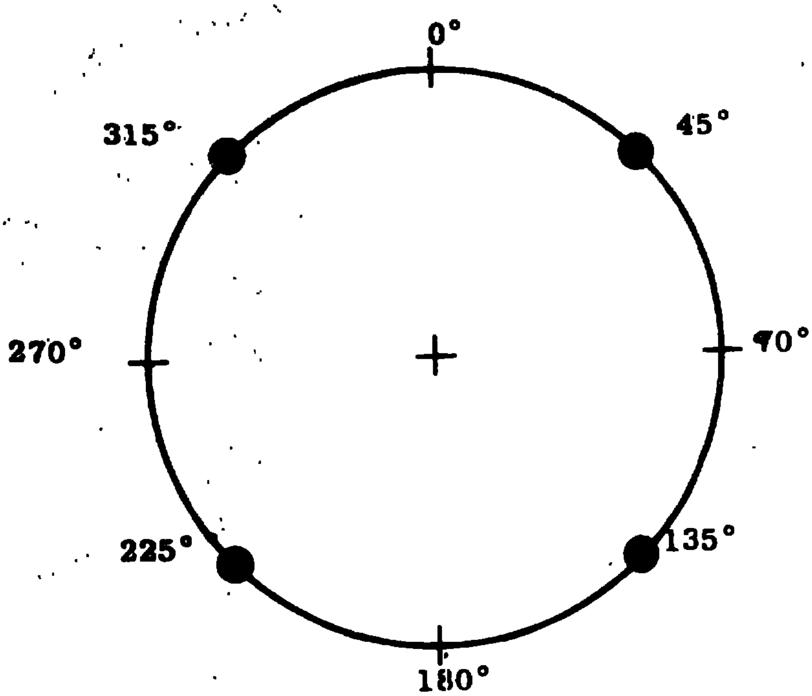
Static Pressures



Skin Temperatures

Venturi Throat (looking upstream)

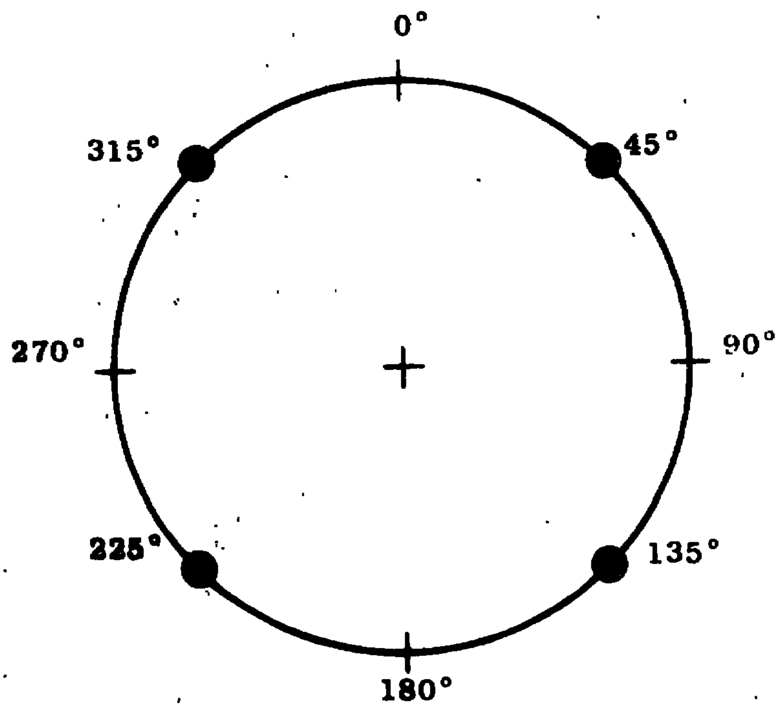
Figure 3. Test Instrumentation Locations



4 taps to a manifold PSA

Static Pressure Upstream of Conical Screen (Venturi downstream plenum)

Looking upstream

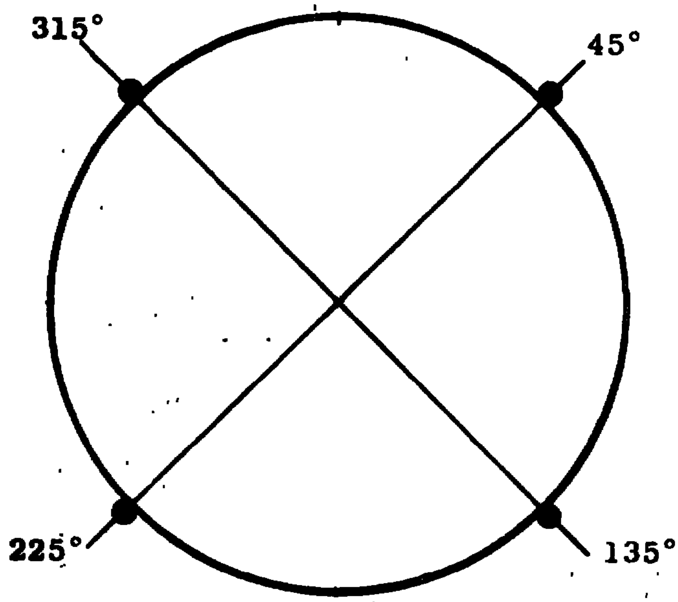


4 taps to a manifold

Static Pressure Downstream of Conical Screen for ΔP Alarm only. (12 ft. dia.)

Figure 3 (Cont'd)

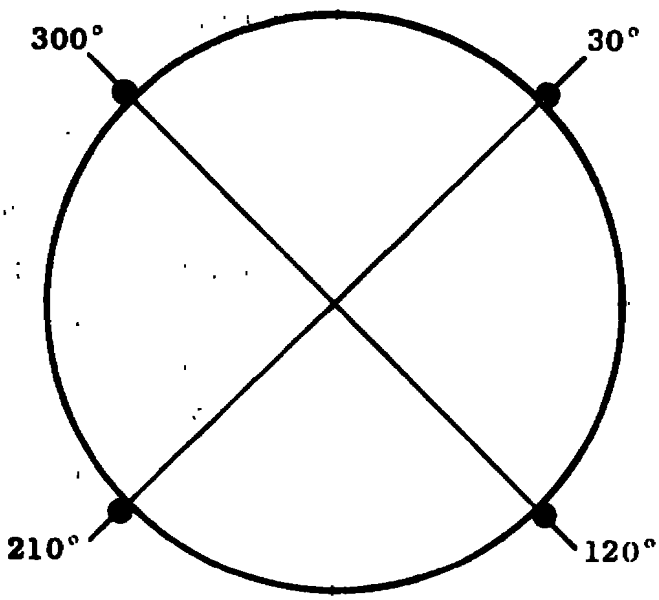
UNCLASSIFIED



4 taps to
a manifold

PSB

Static Pressure at Sta. B, (8 ft. dia. duct)



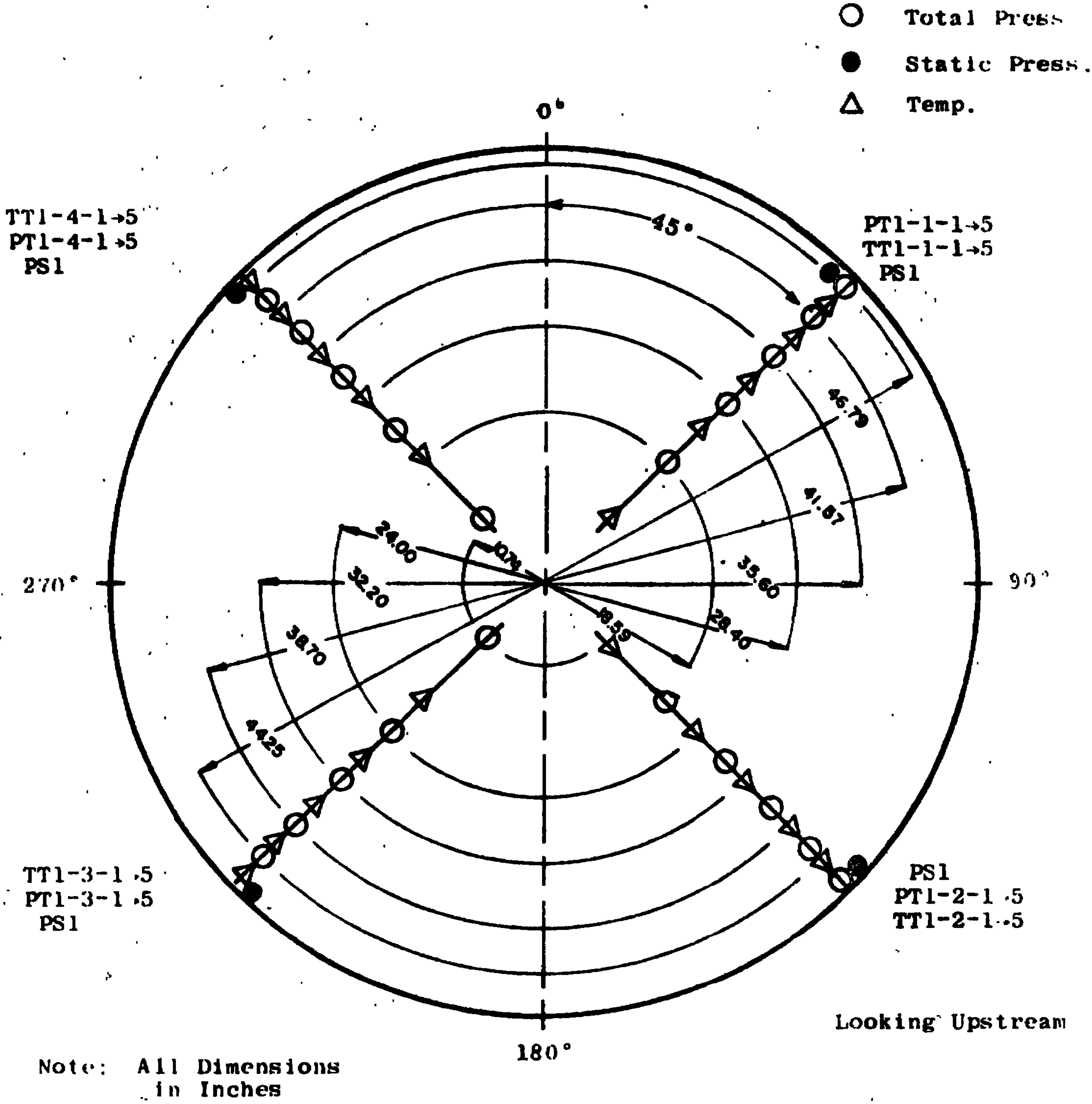
4 taps to
a manifold

PSBMI

Looking upstream

Static Pressure at Sta. C (3 ft. dia. duct)

FIG. 3 (con't)



J-2 8' Duct Pressure & Temp Probe Location (Station 1)

Test Cell Instrumentation

FIG. 3 (cont'd)

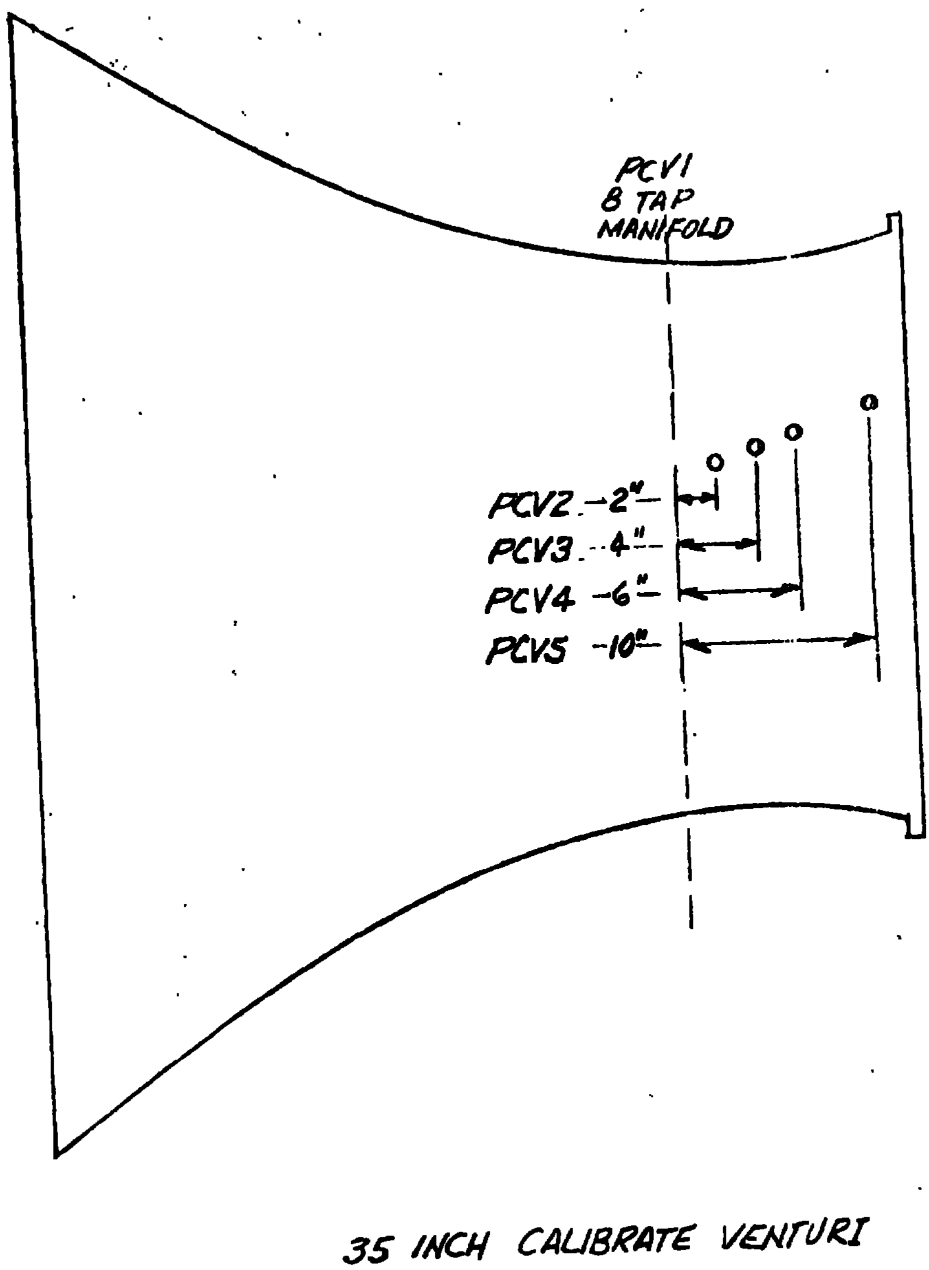


Figure 4. Reference Venturi Instrumentation

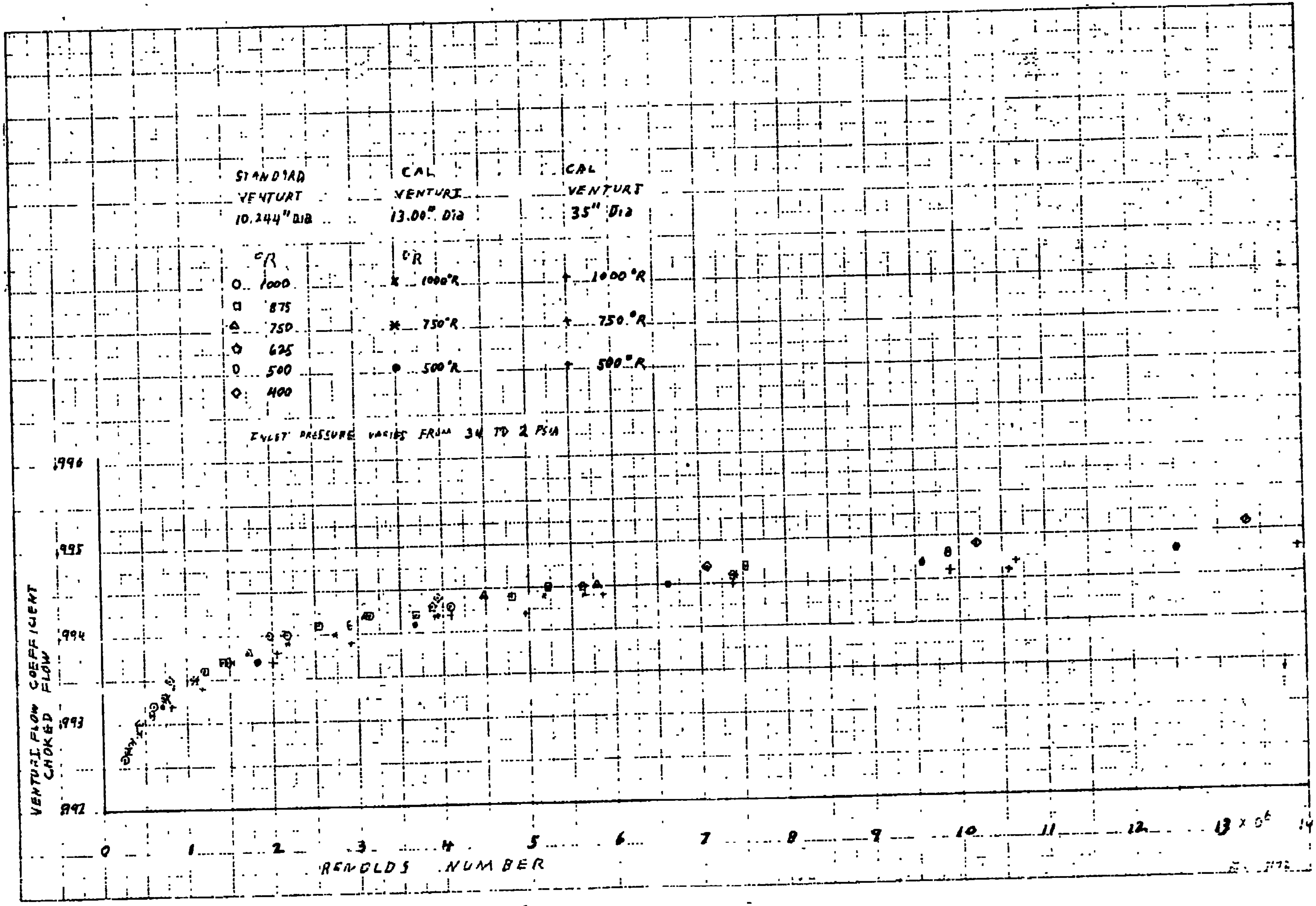


Figure 5 Venturi Choked Flow Coefficient

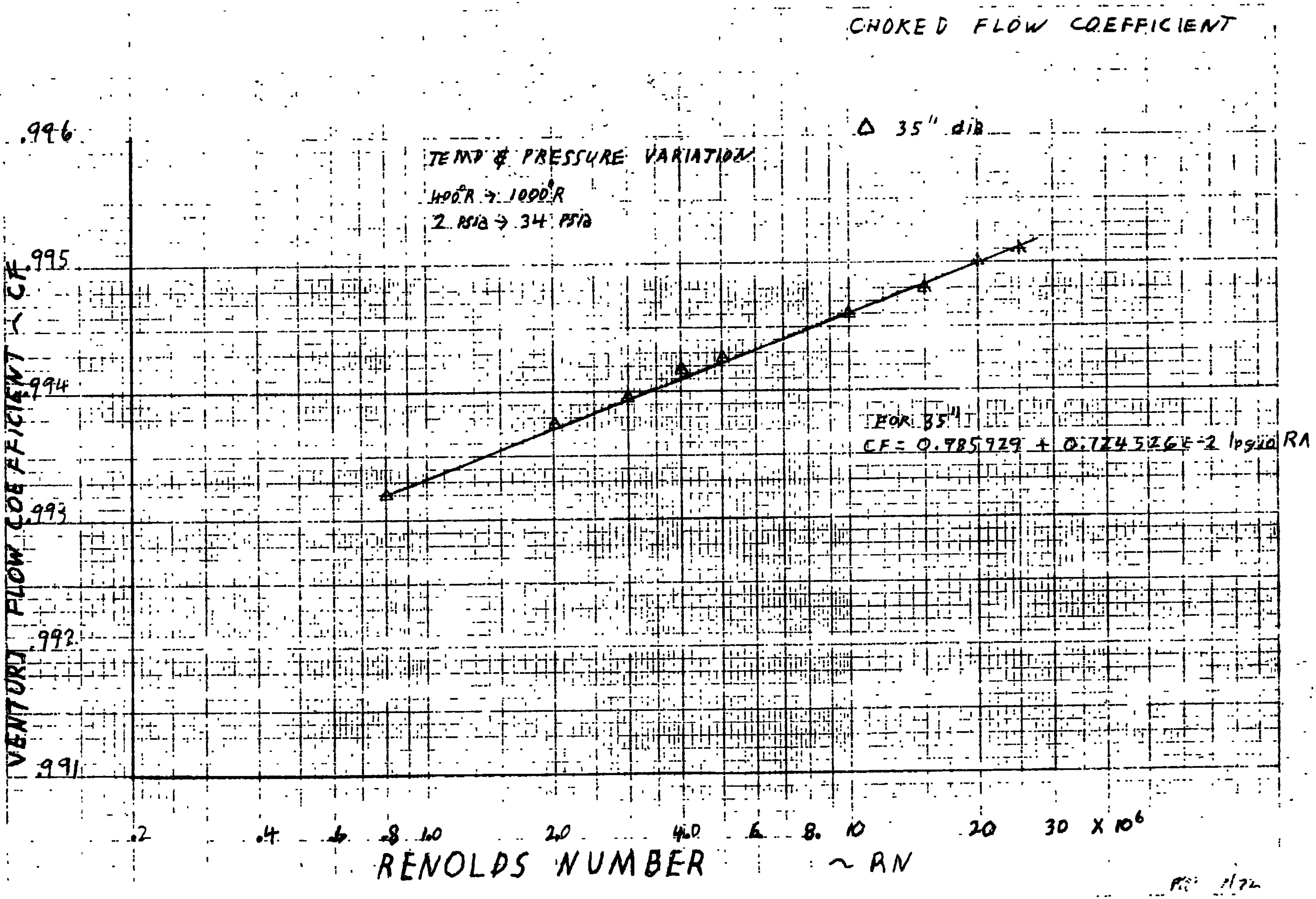


Figure 6. Venturi Choked Flow Coefficient

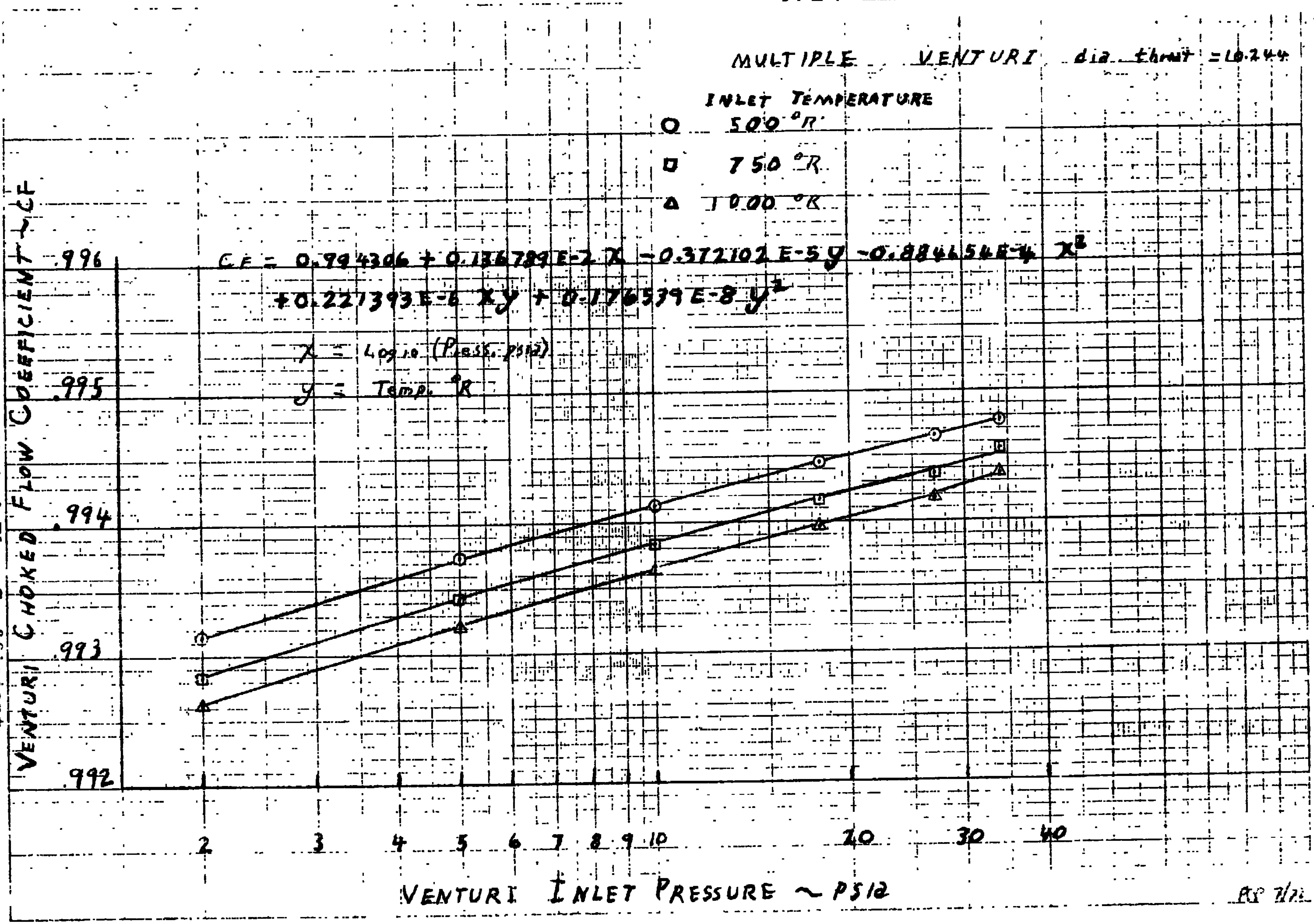


Figure 7. Venturi Choked Flow Coefficient Surface Fit

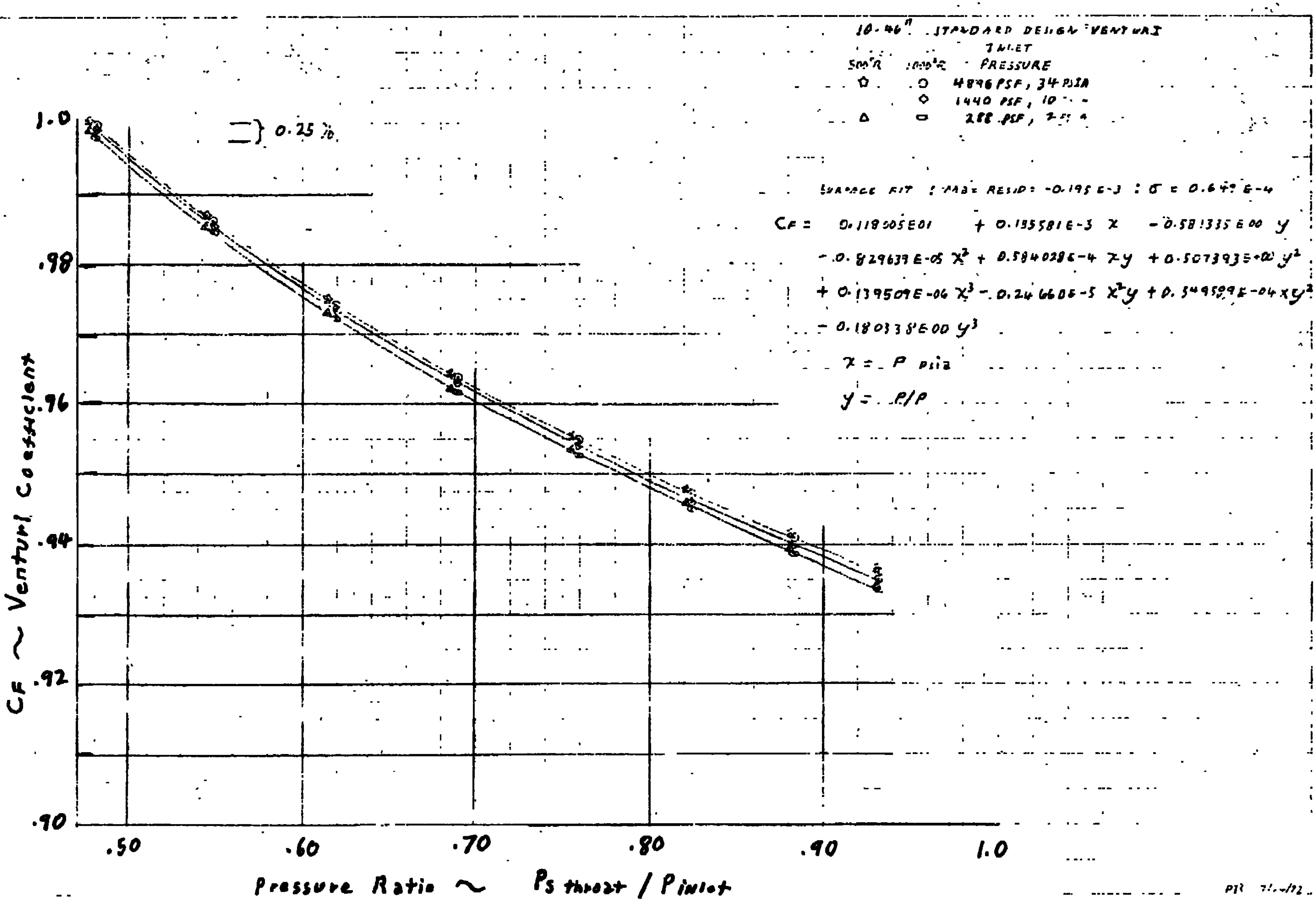


Figure 8. Venturi Unchoked Flow Coefficient Surface Fit

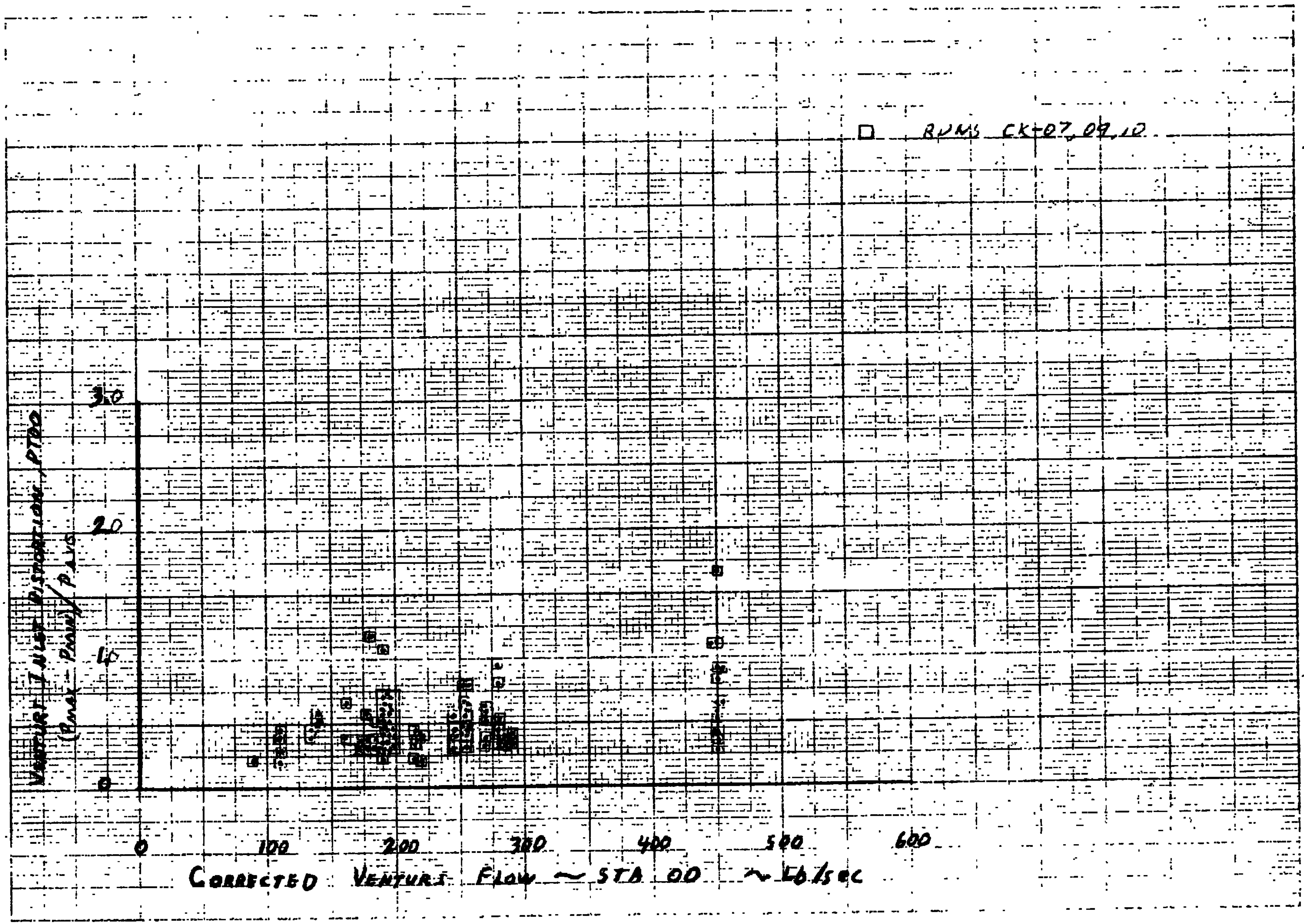


Figure 9. Station 00 Pressure Distortion

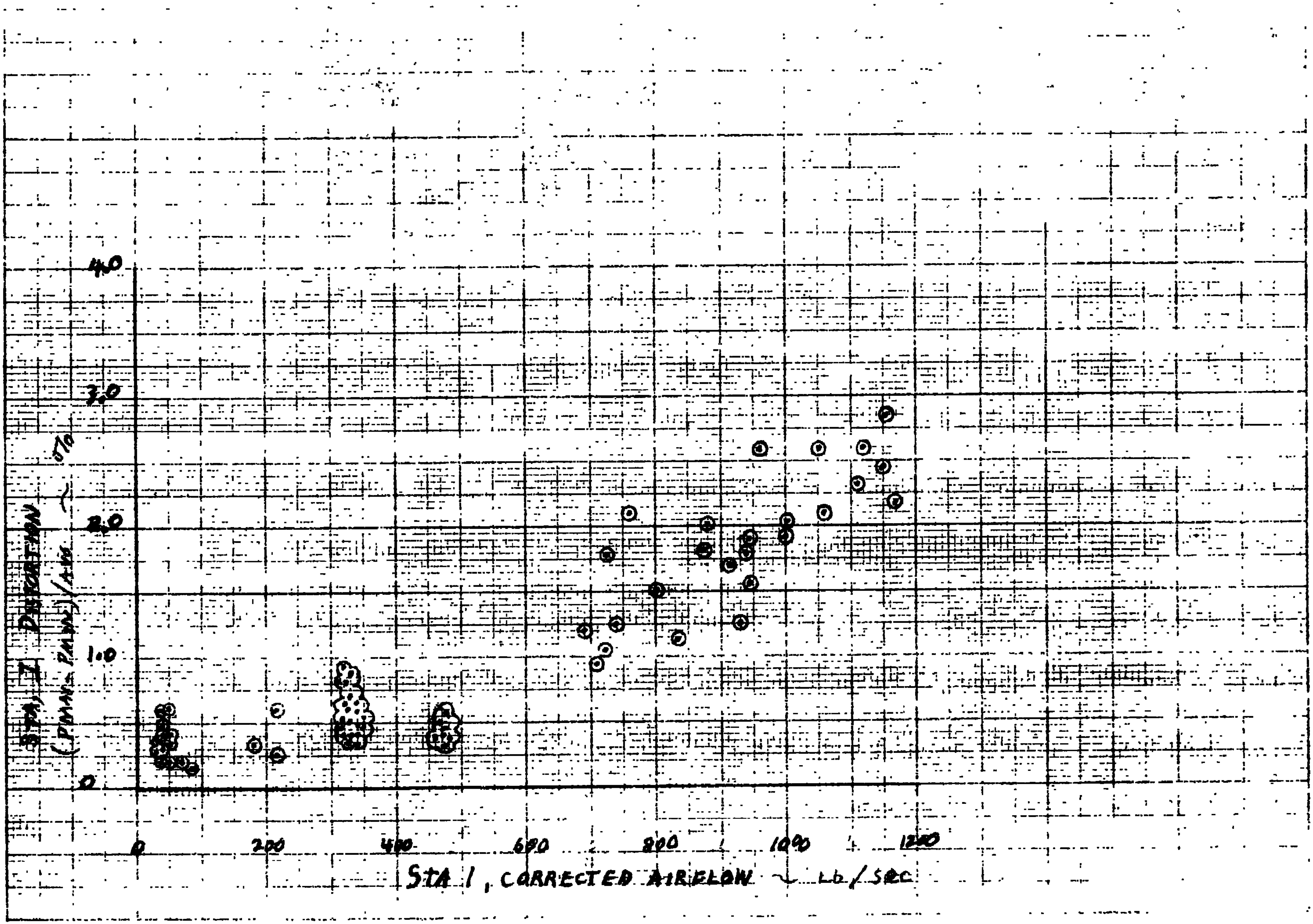


Figure 10. Station 1 Pressure Distortion

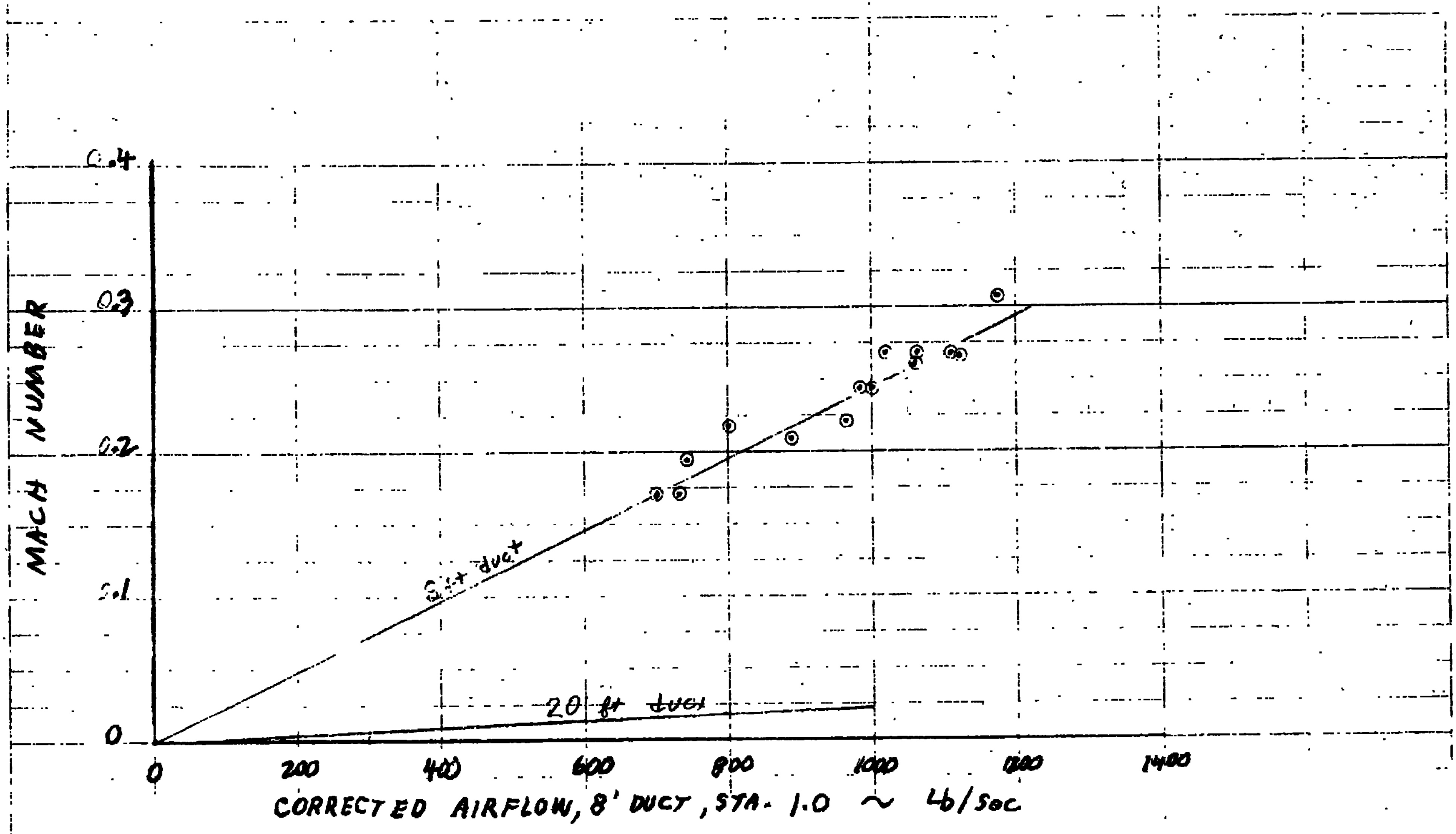


Figure 11. Duct Mach Number

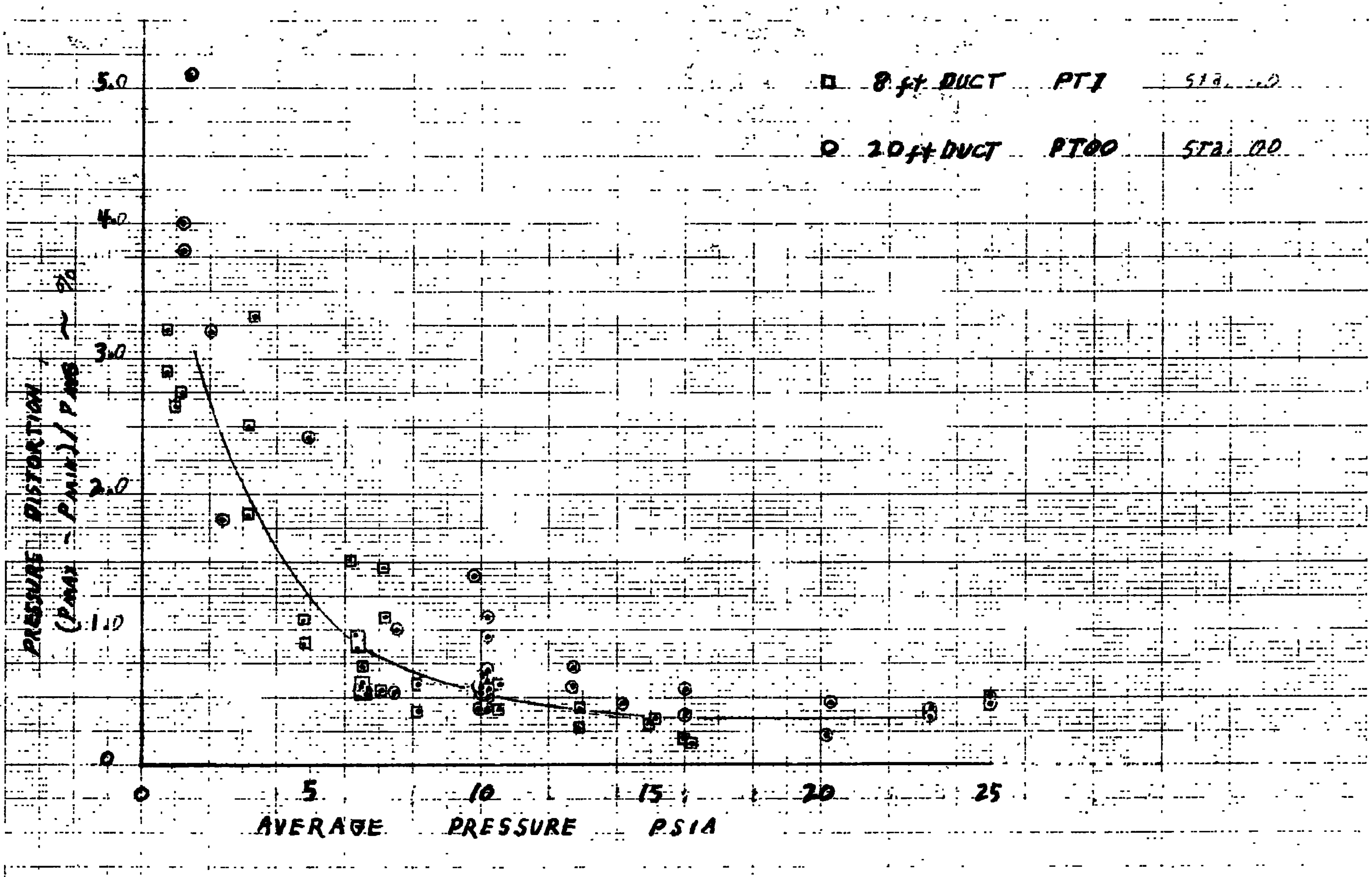


Figure 12. Pressure Distortion vs Pressure Level

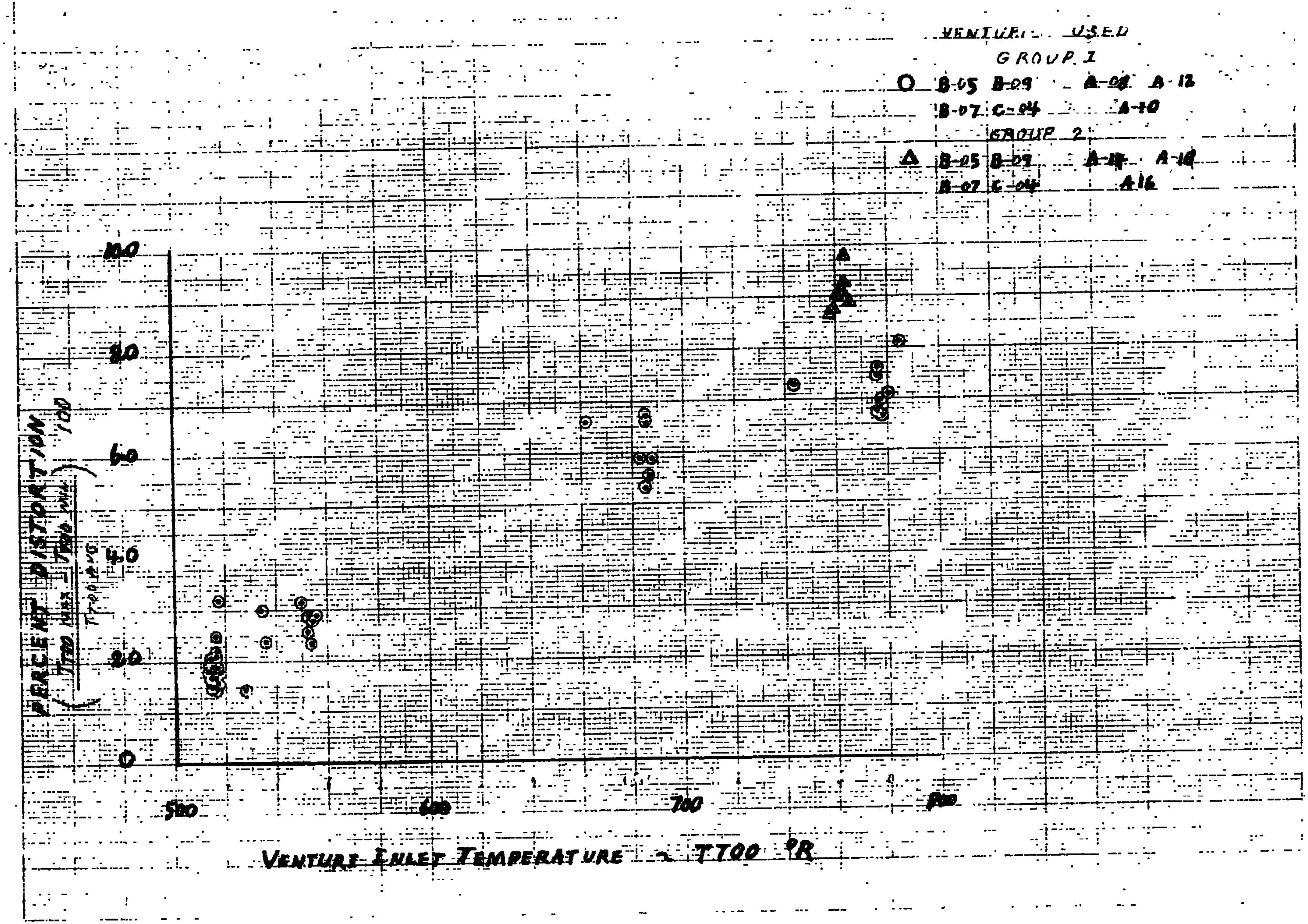


Figure 13. Temperature Distortion

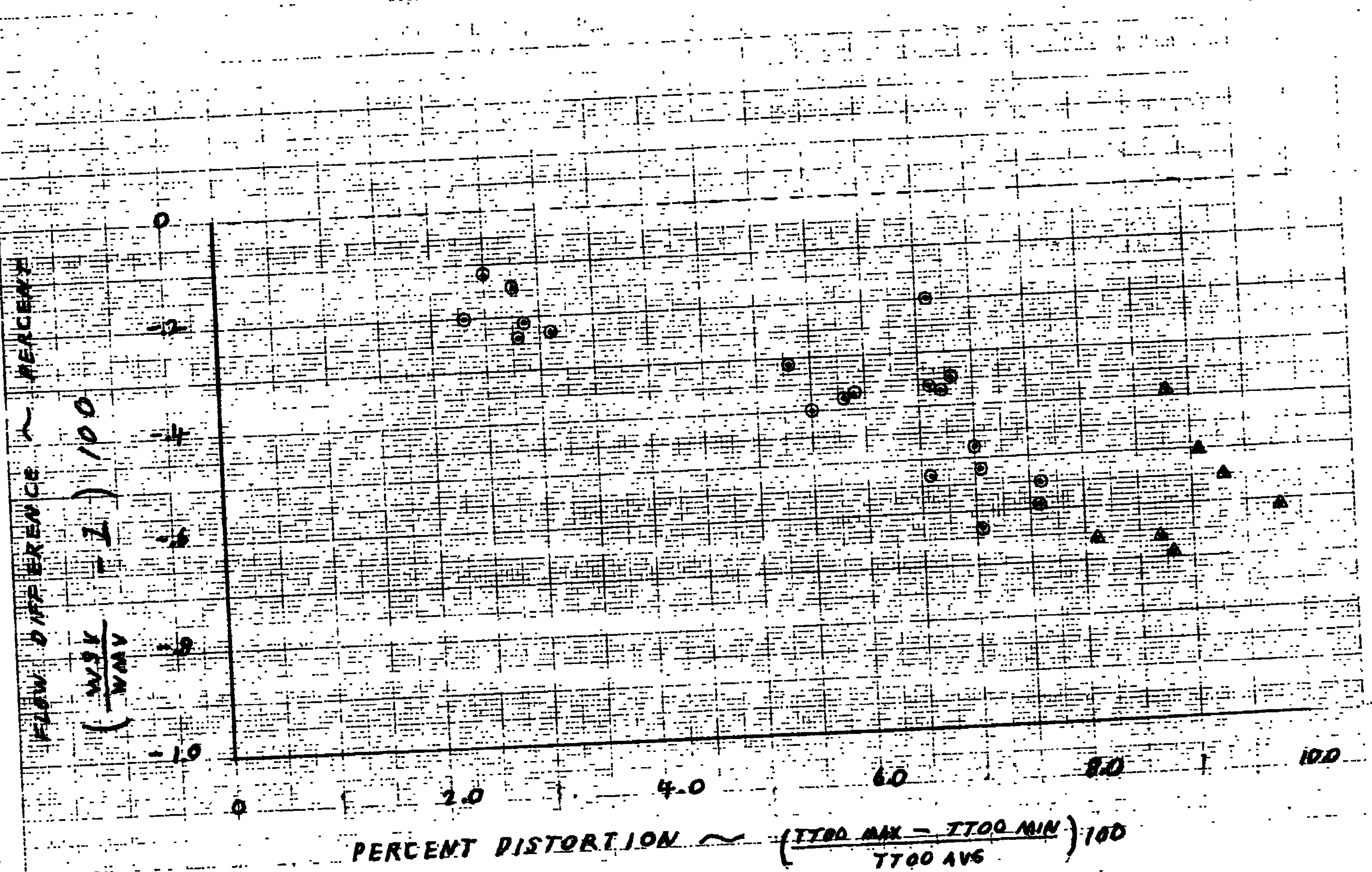


Figure 14. Effect of Temperature Distortion on Flowrate Computation

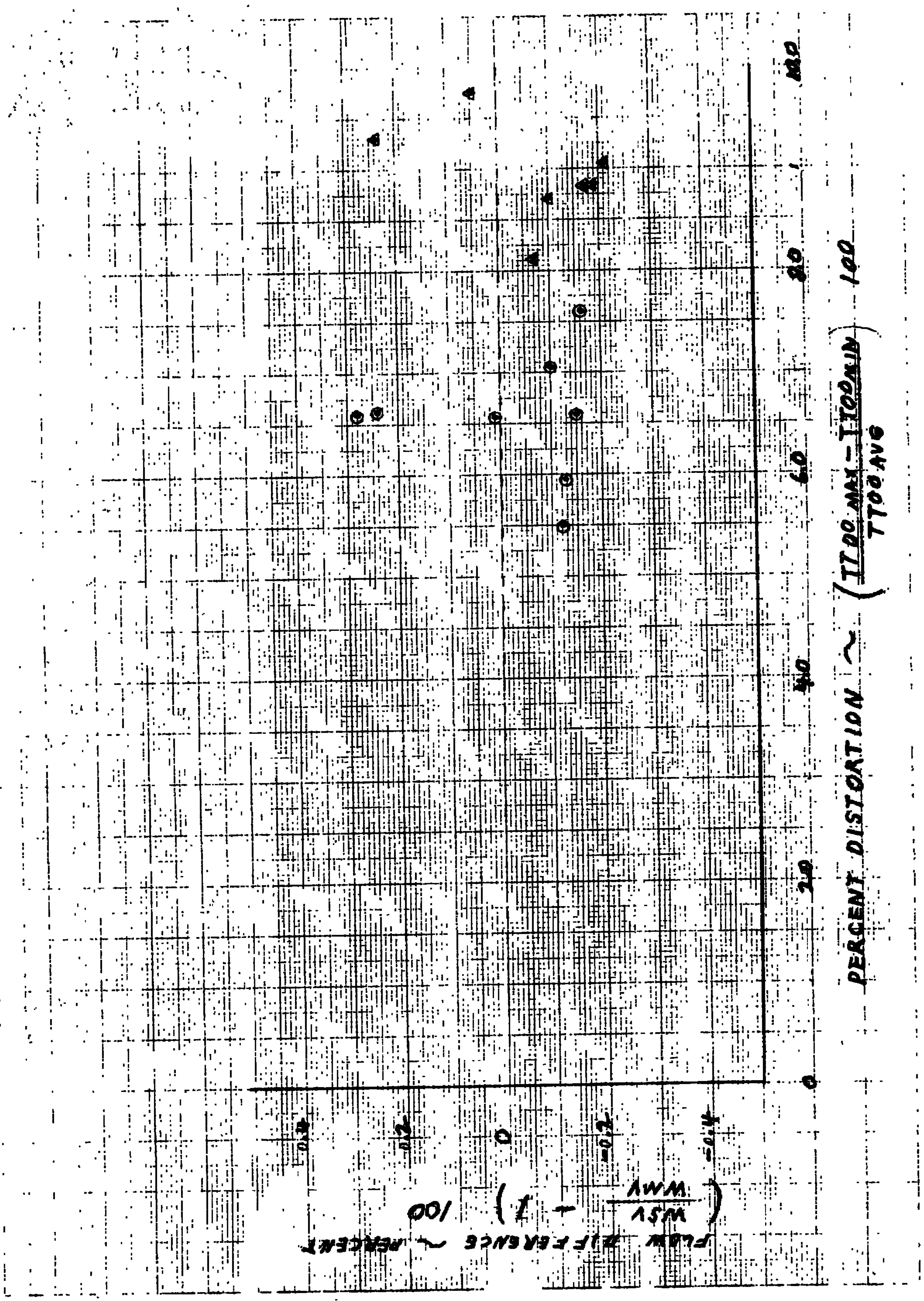


Figure 15. Flowrate Computation with Adequate Temperature Sampling

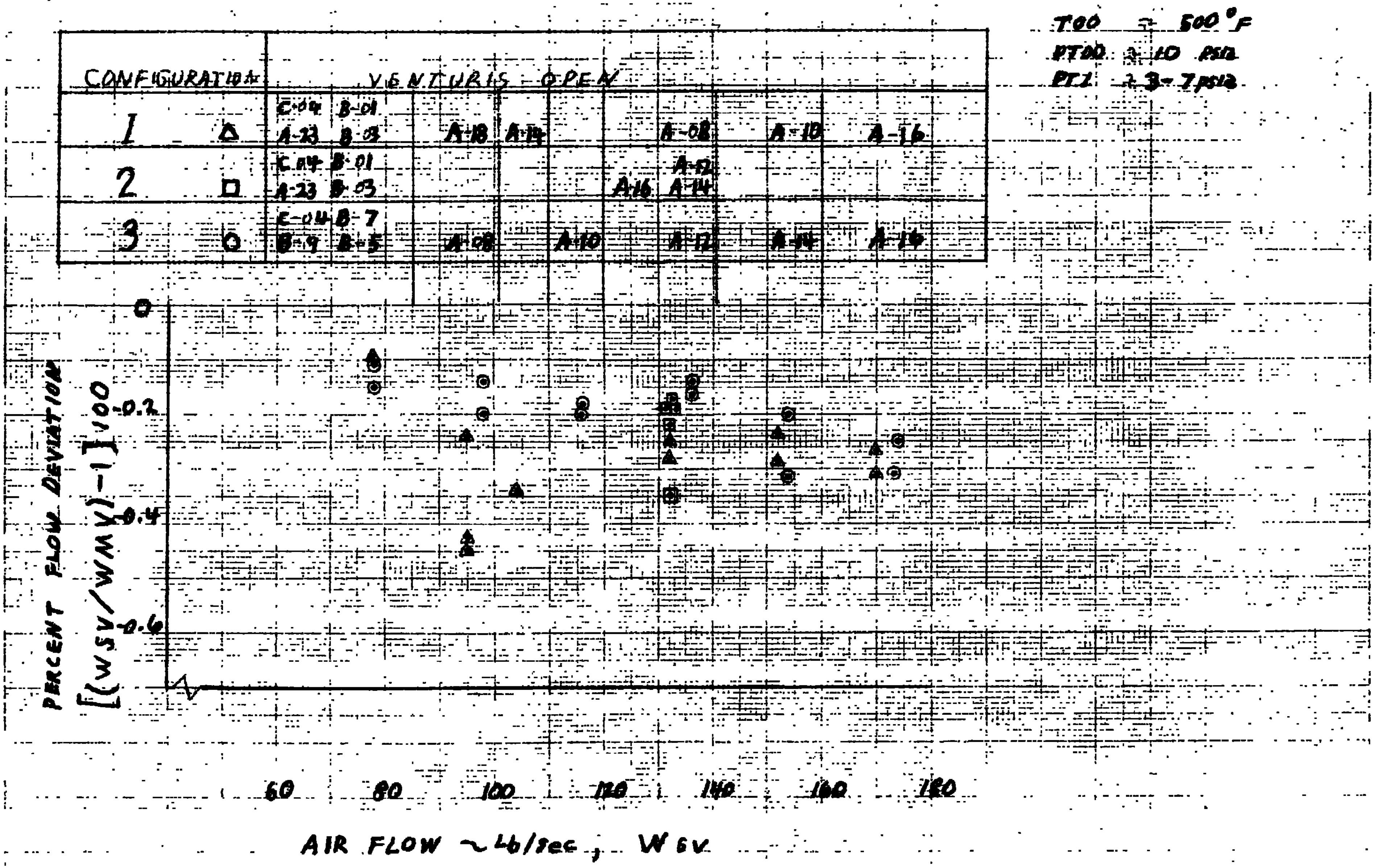


Figure 16. Effect of Multiple Venturi Configuration on Airflow Measurement

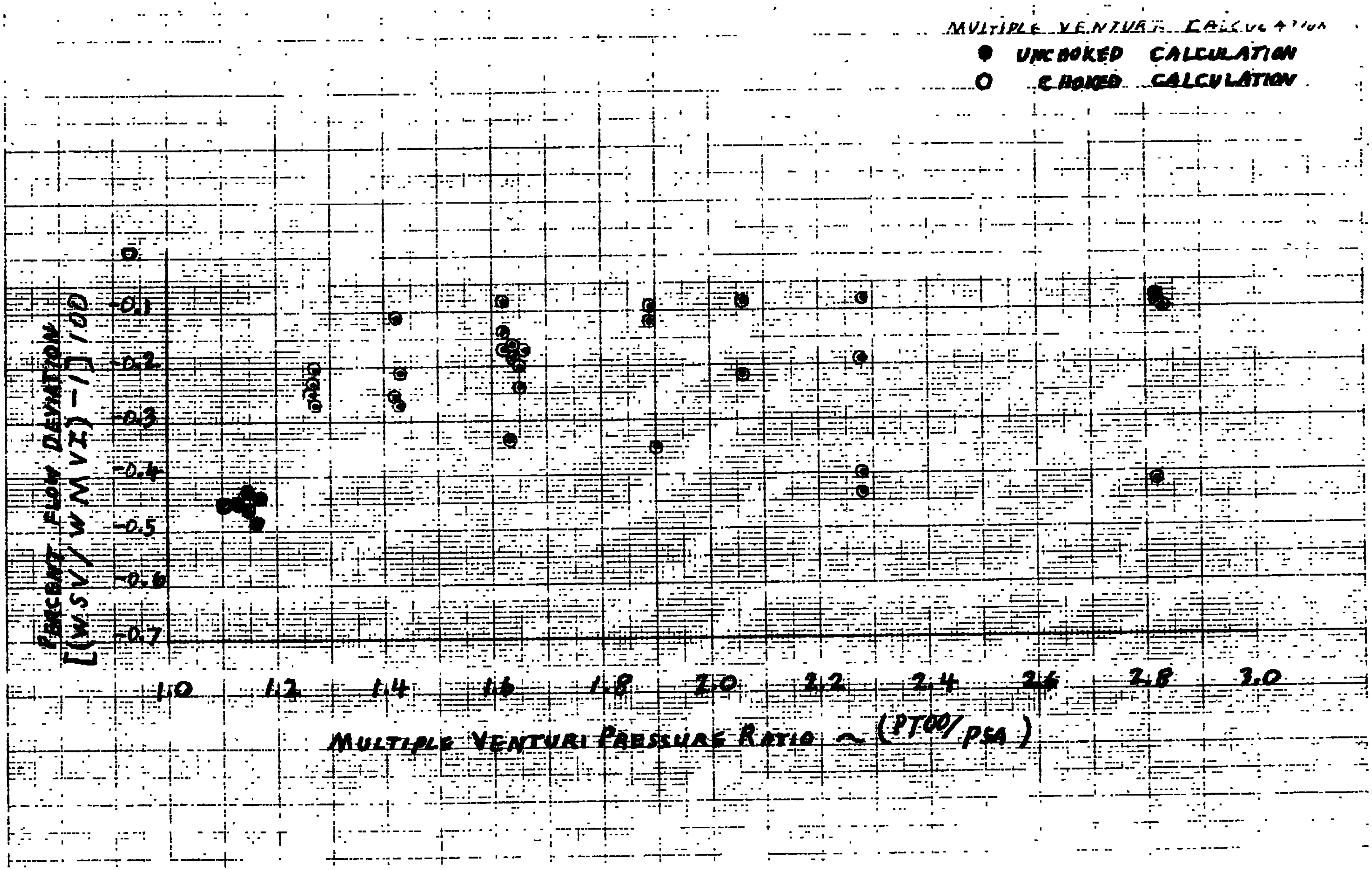


Figure 17. Multiple Venturi Flow vs Reference Venturi Flow

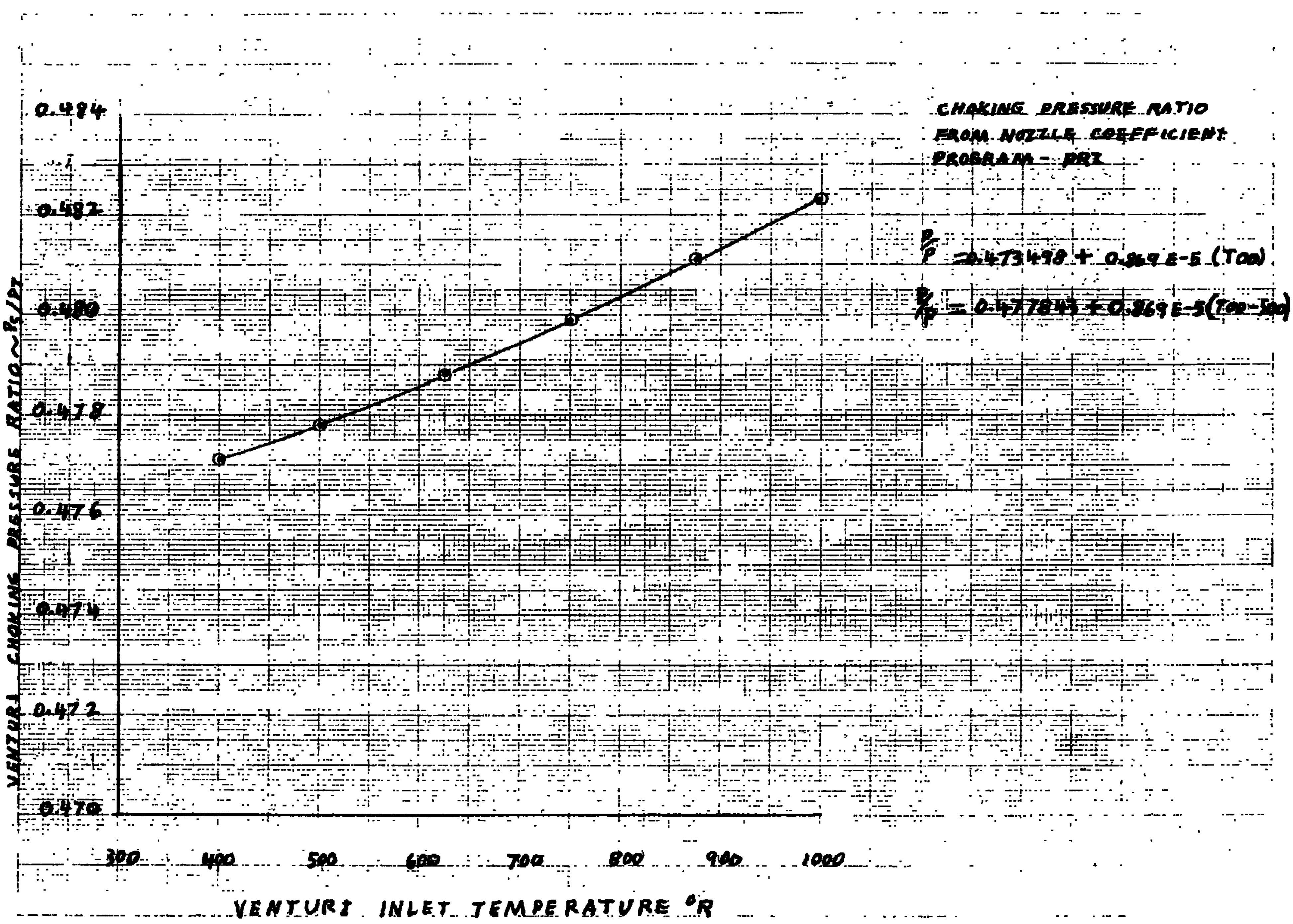


Figure 18. Venturi Choking Pressure Ratio vs Temperature

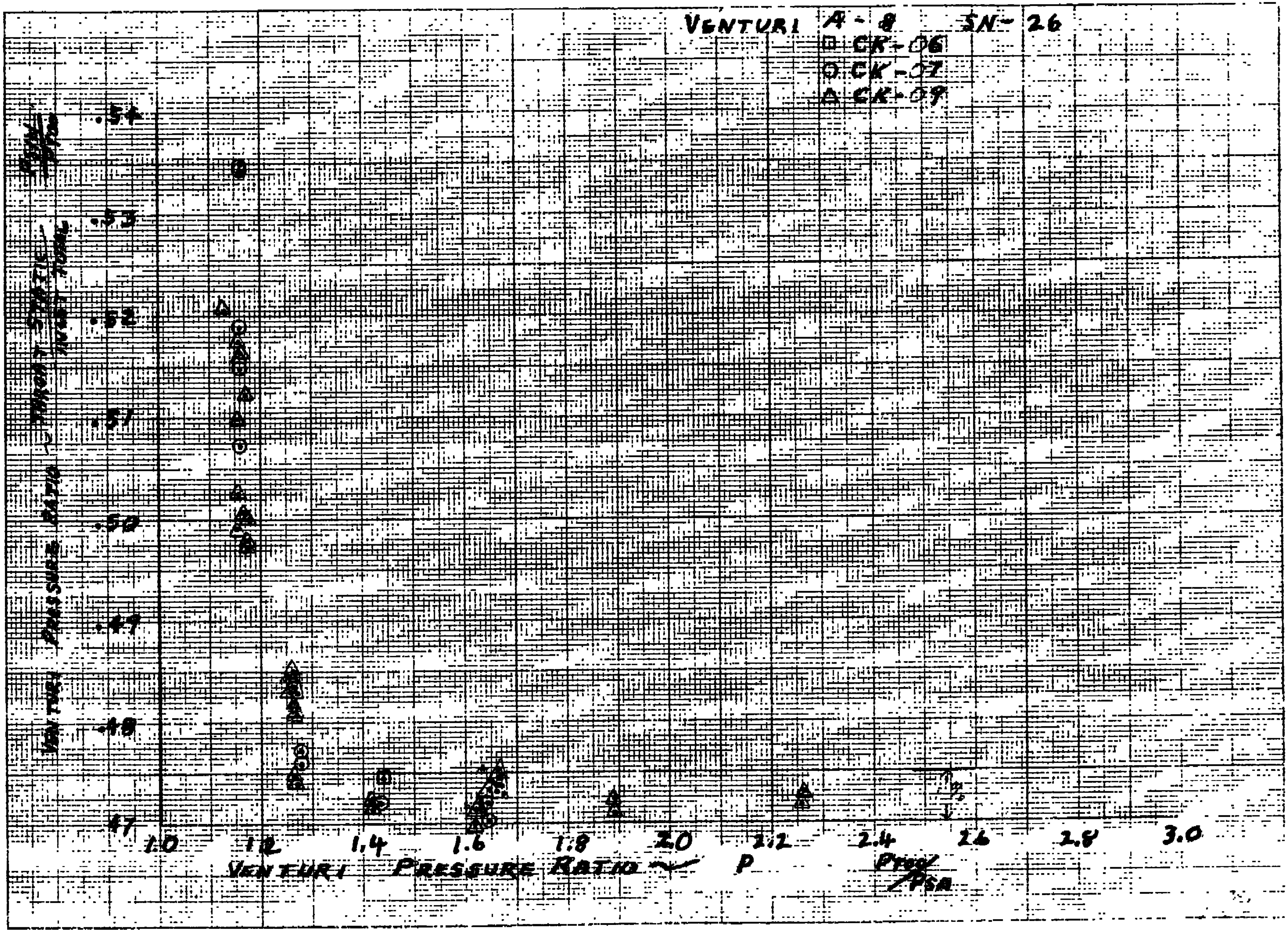


Figure 19. Venturi Pressure Ratio Characteristics

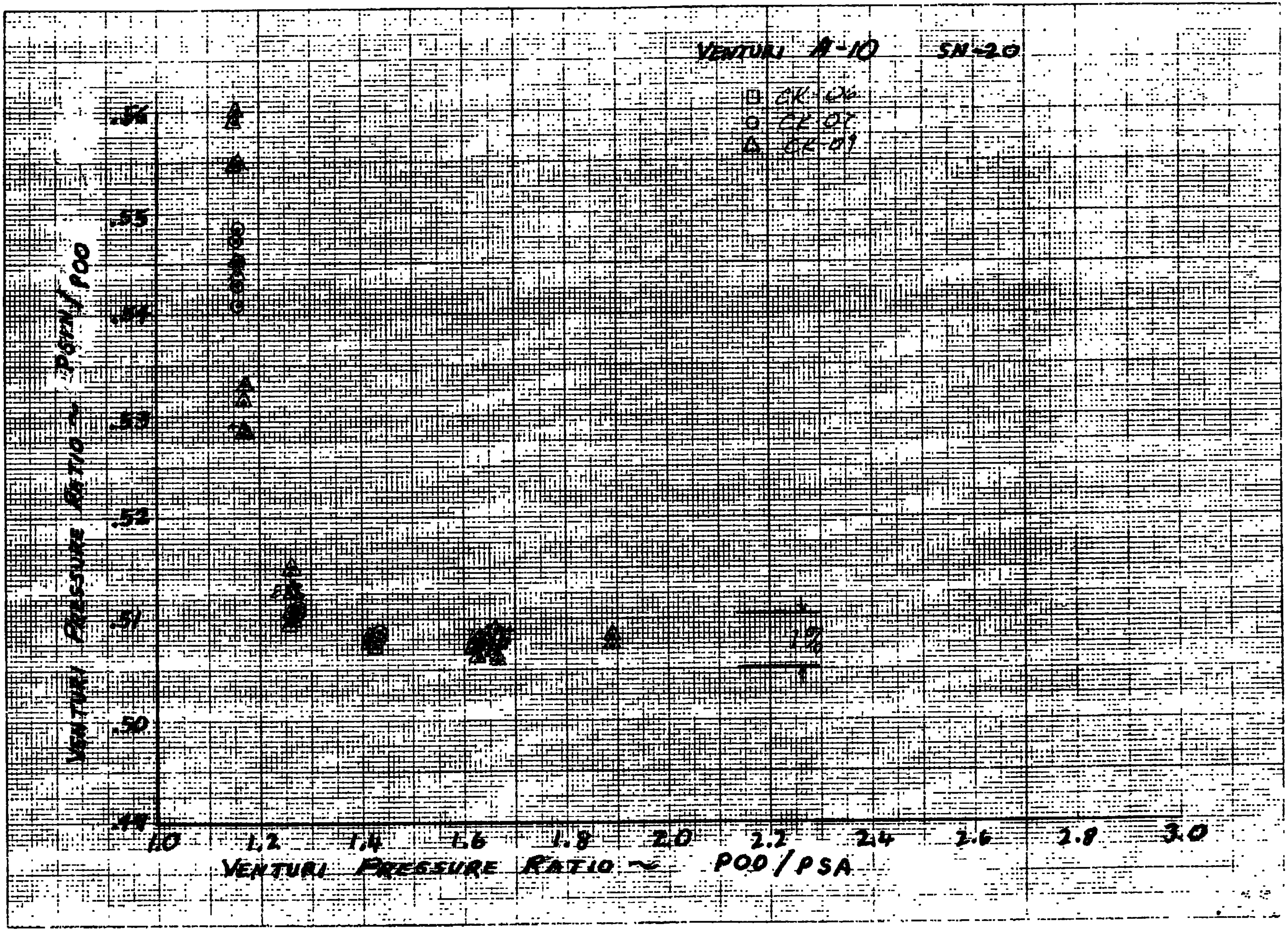


Figure 19 (Cont'd)

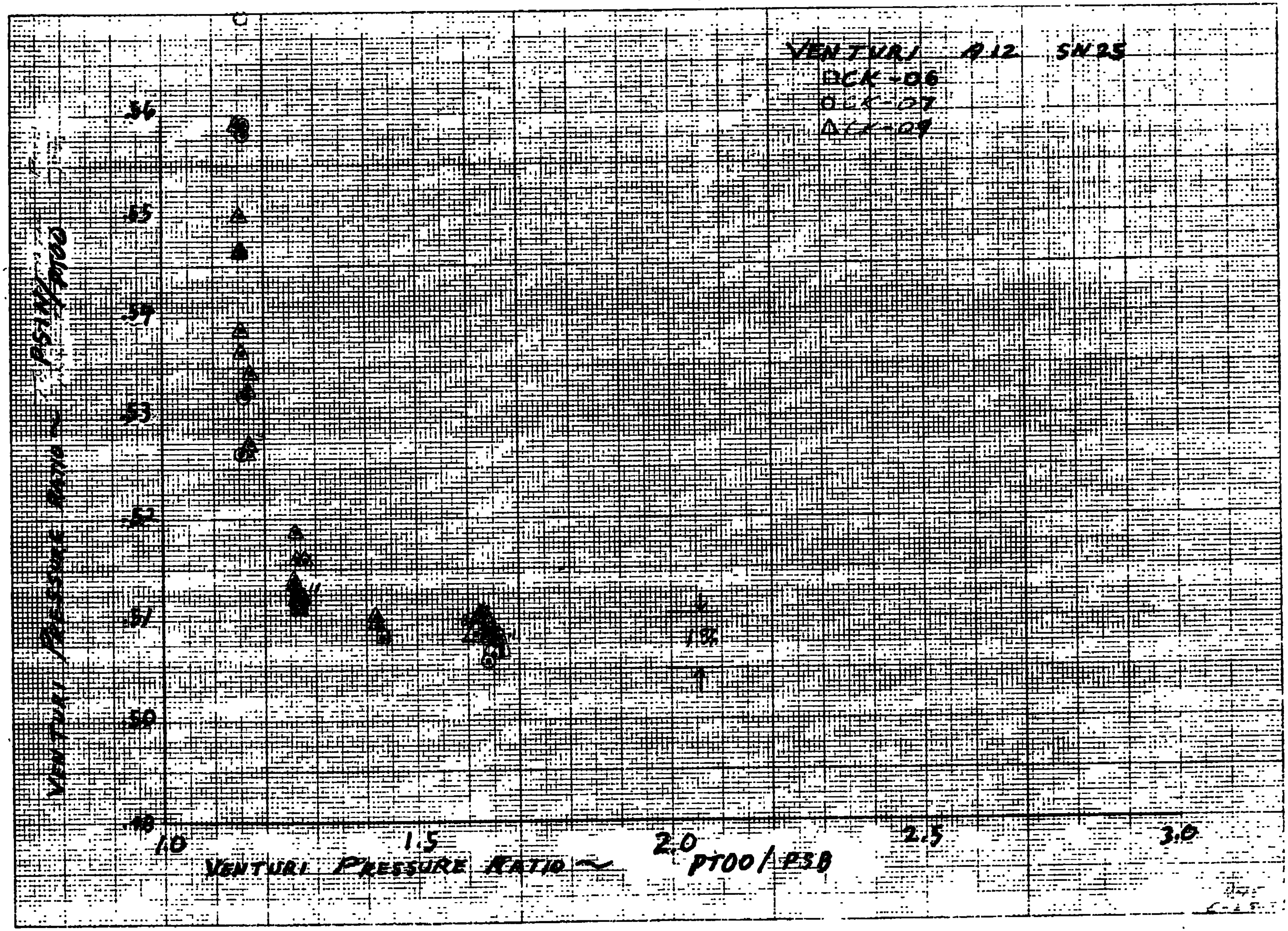


Figure 19 (Cont'd)

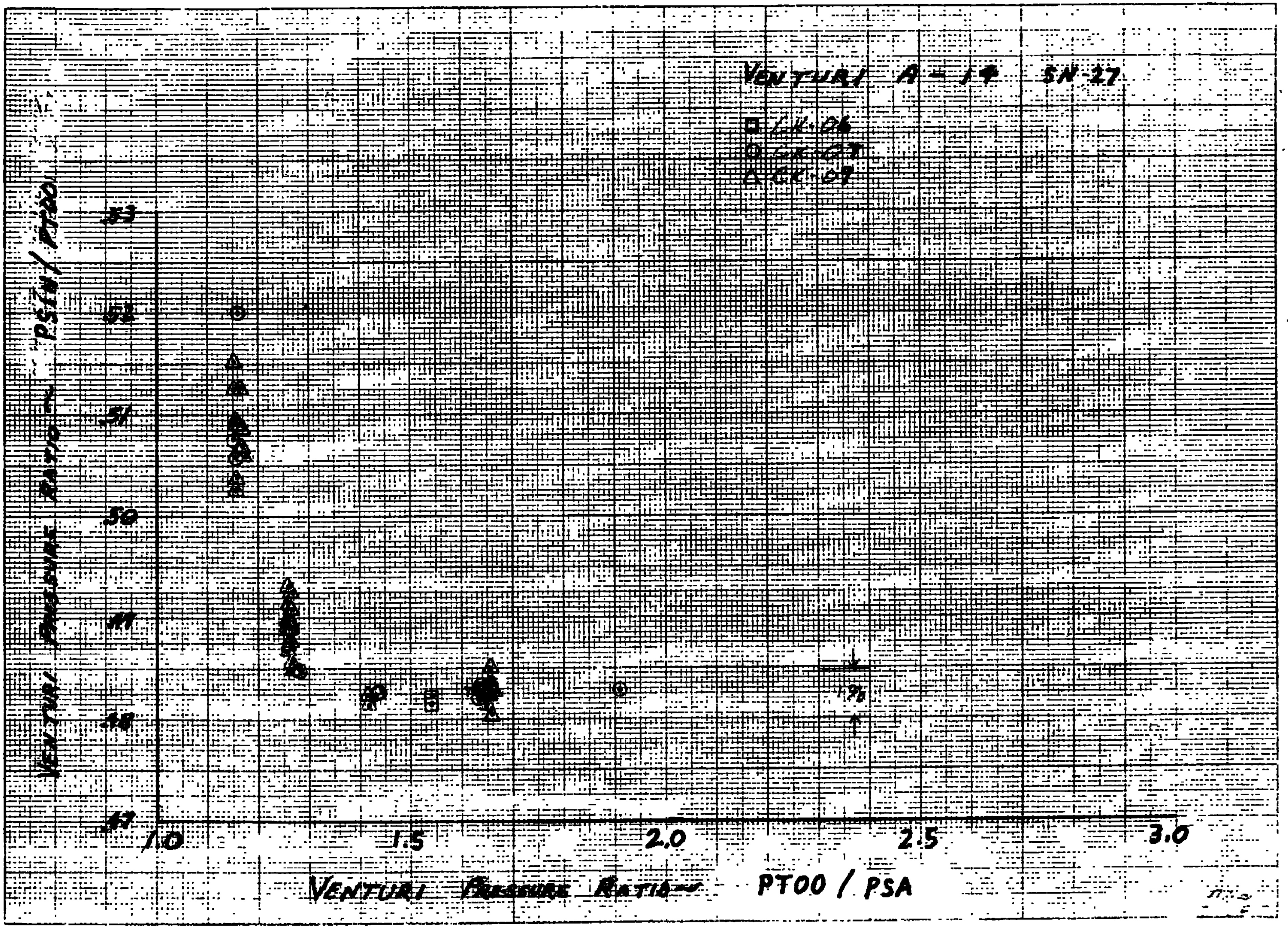


Figure 19 (Cont'd)

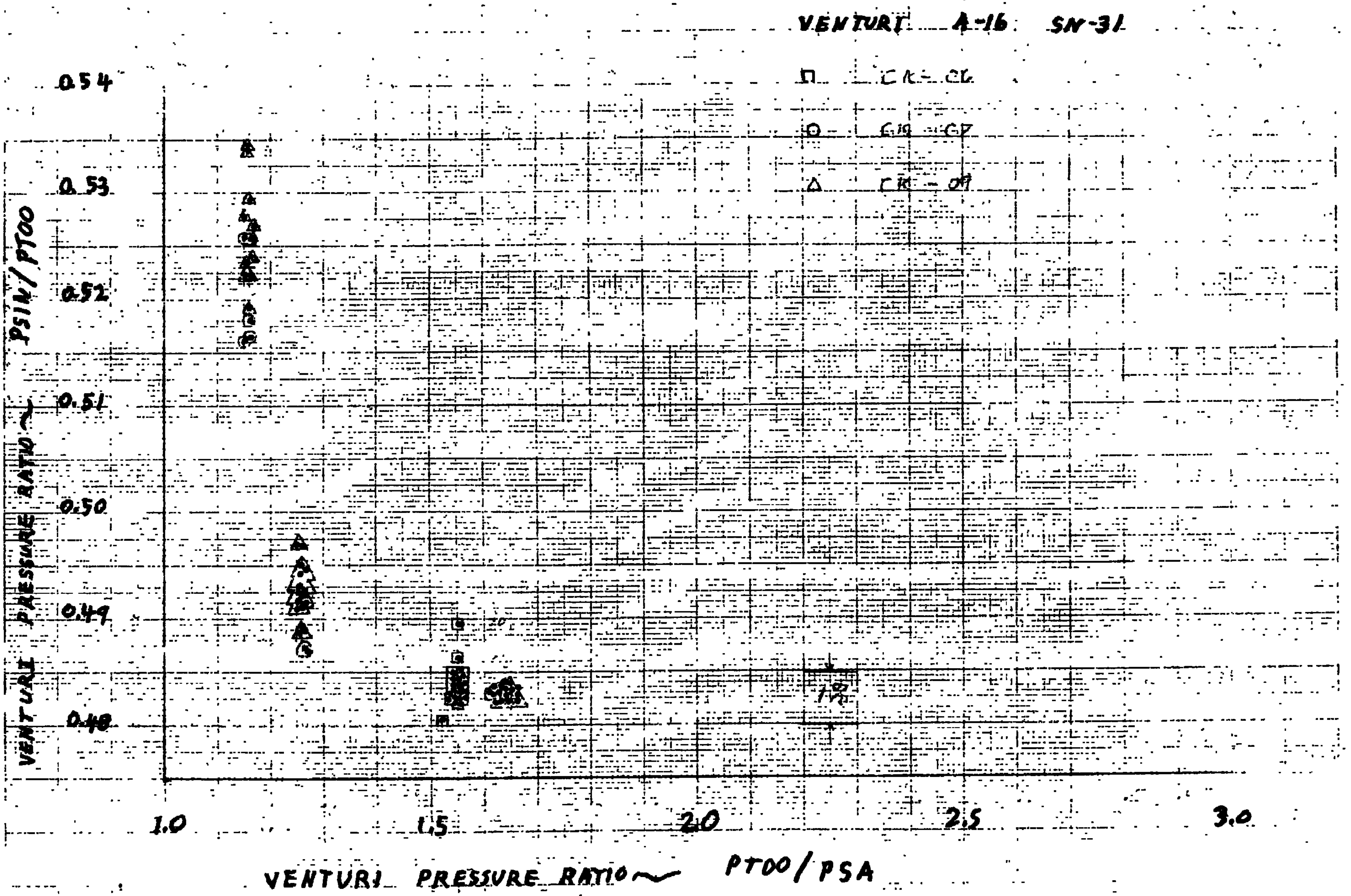


Figure 19 (Cont'd)

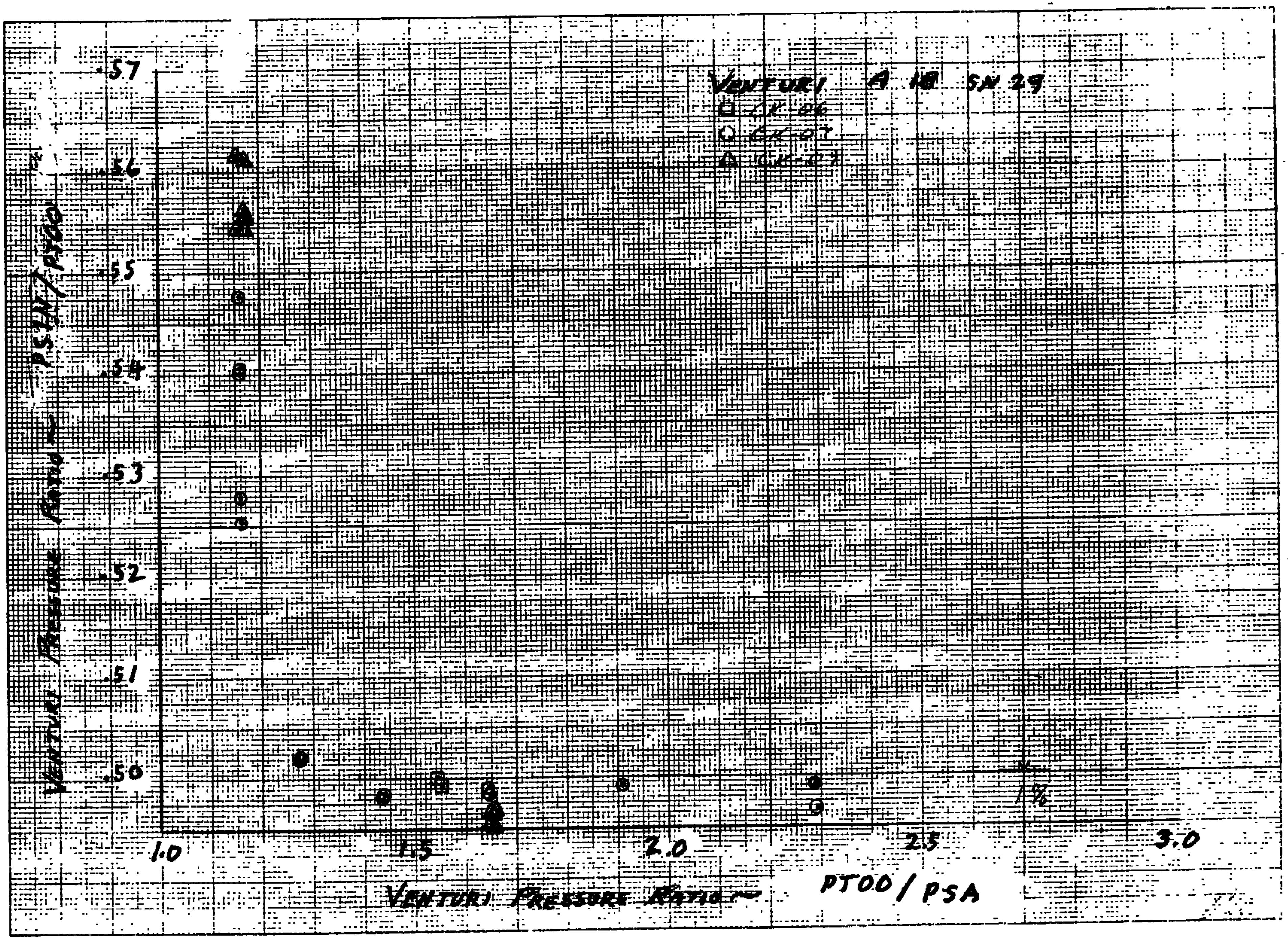


Figure 19 (Cont'd)

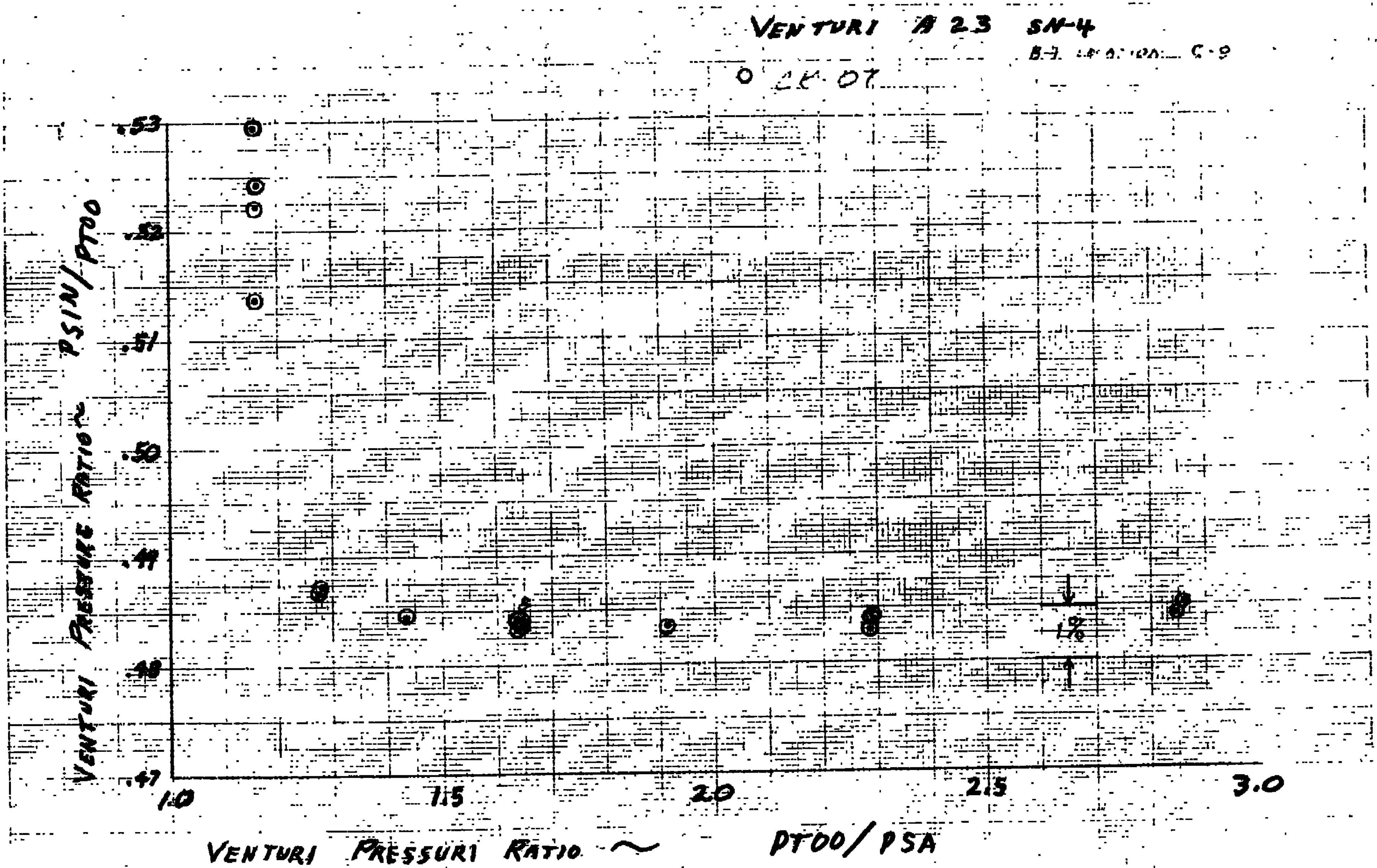


Figure 19 (Cont'd)

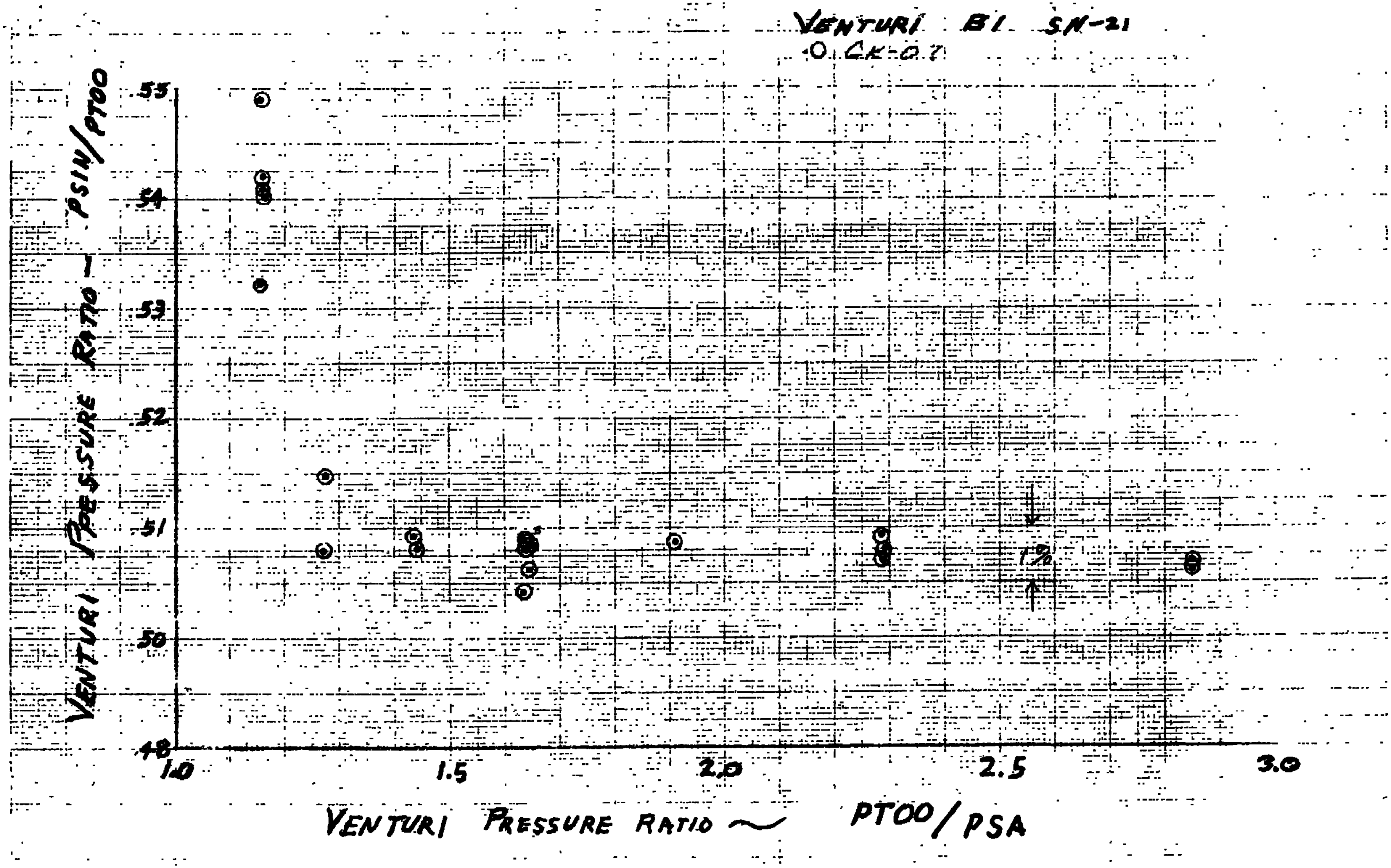


Figure 19 (Cont'd)

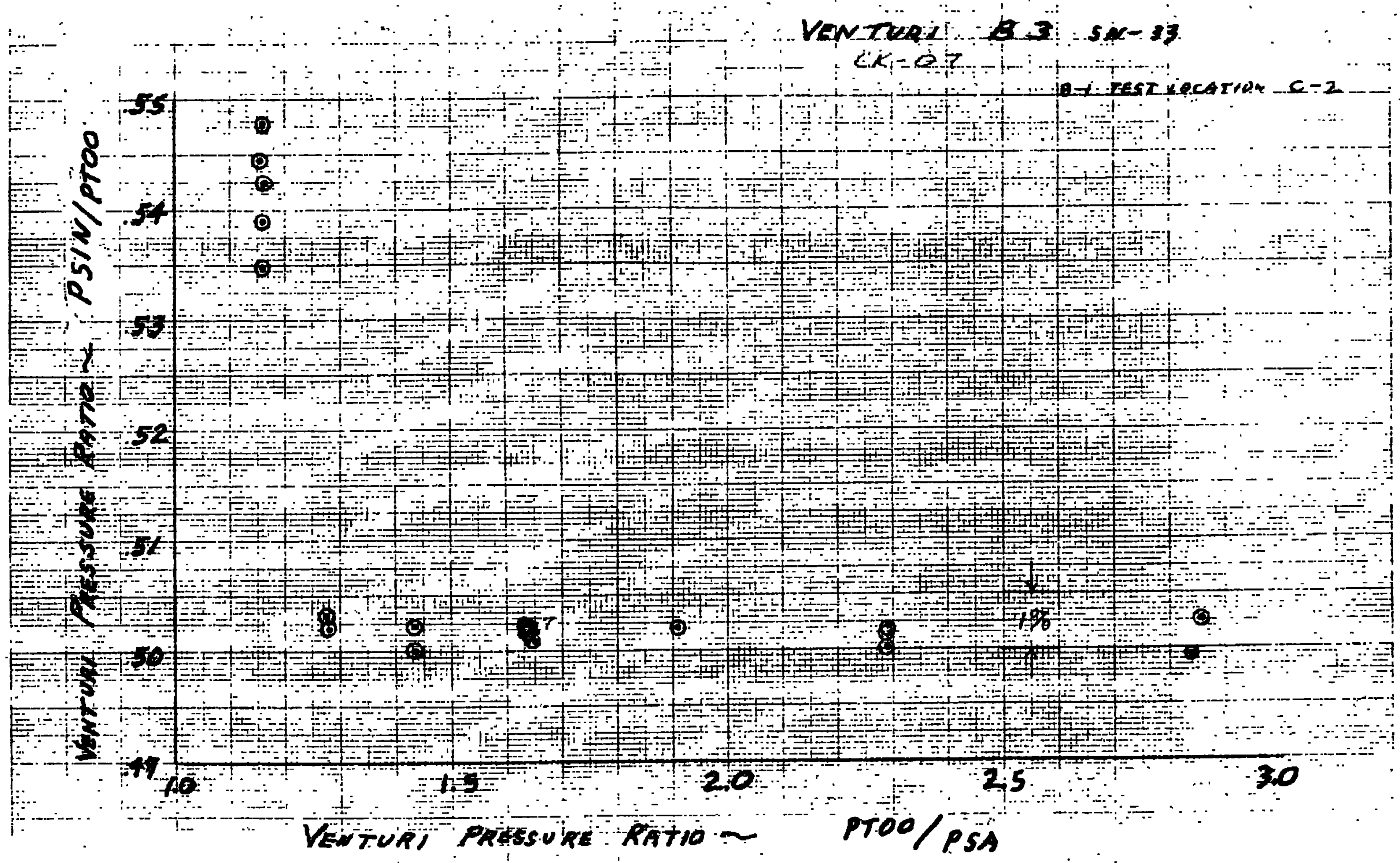


Figure 19 (Cont'd)

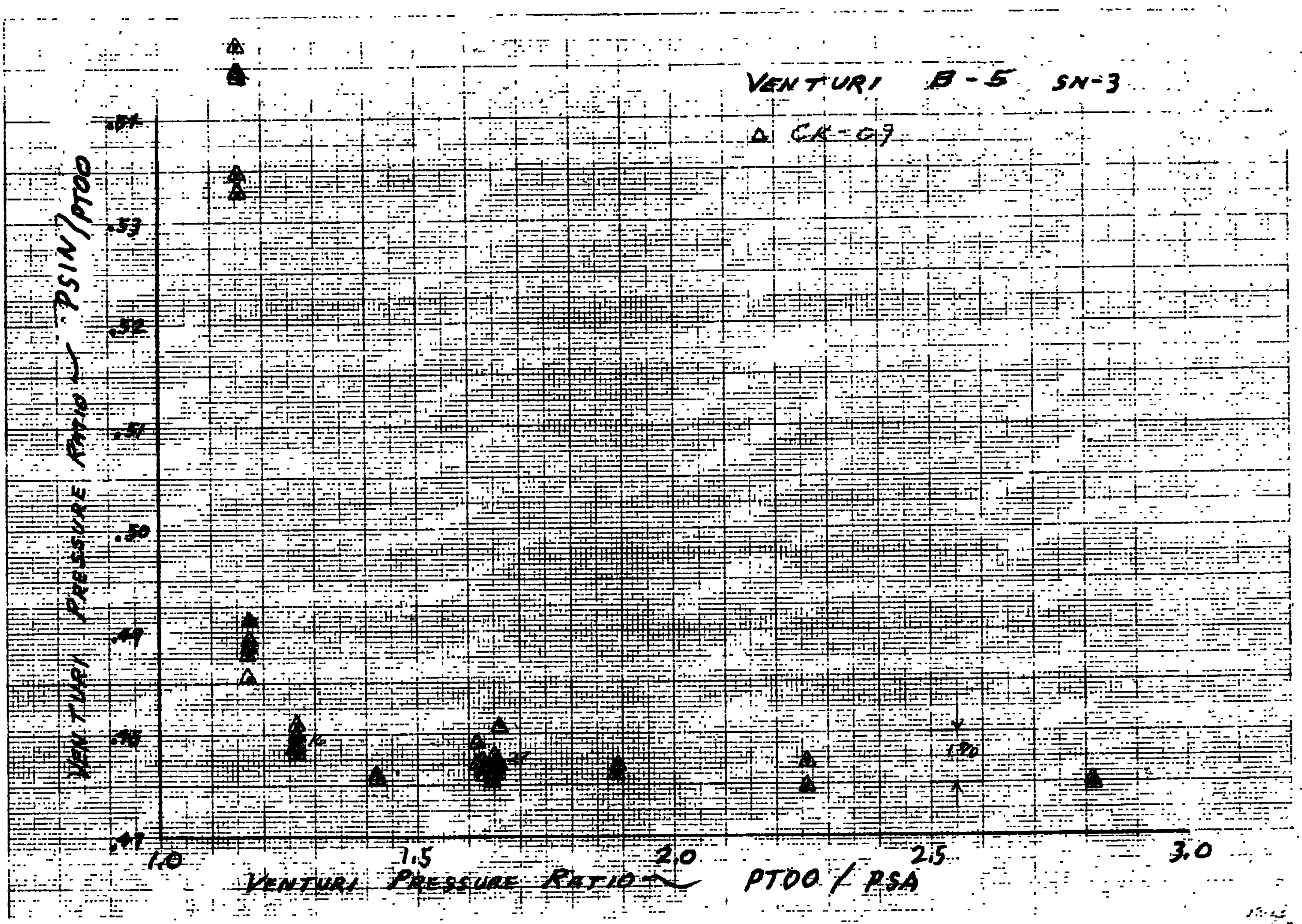


Figure 19 (Cont'd)

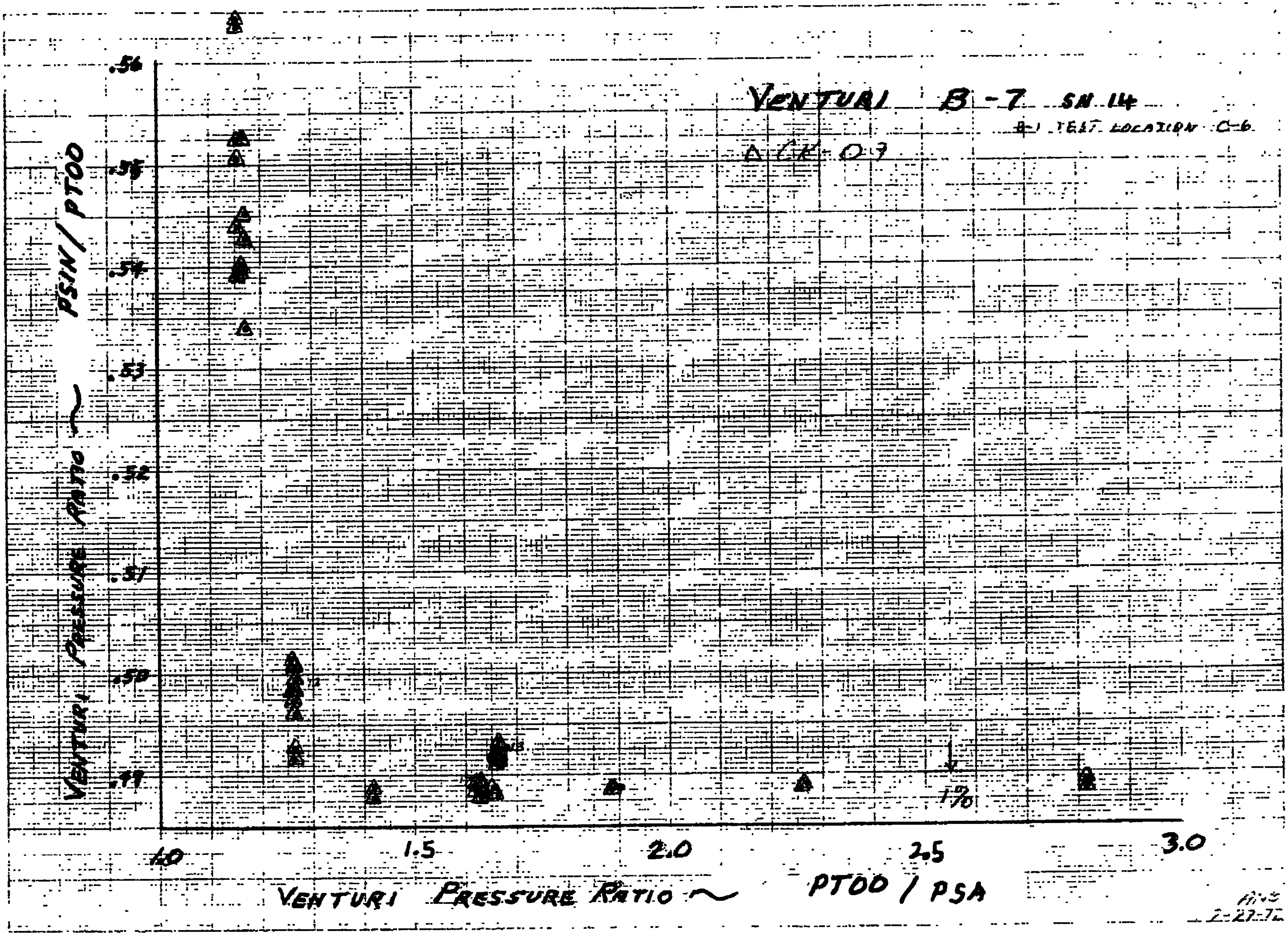


Figure 19 (Cont'd)

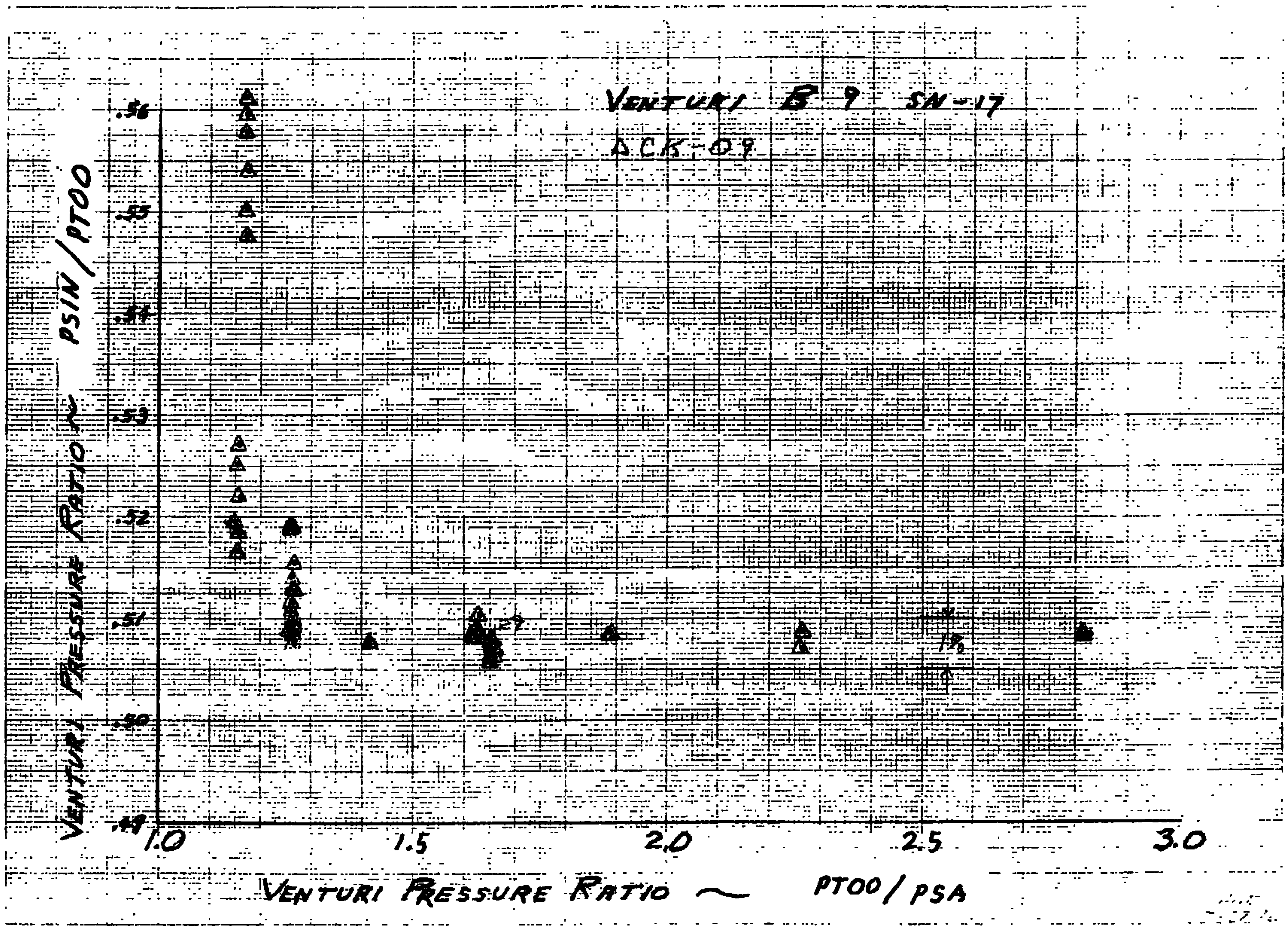


Figure 19 (Cont'd)

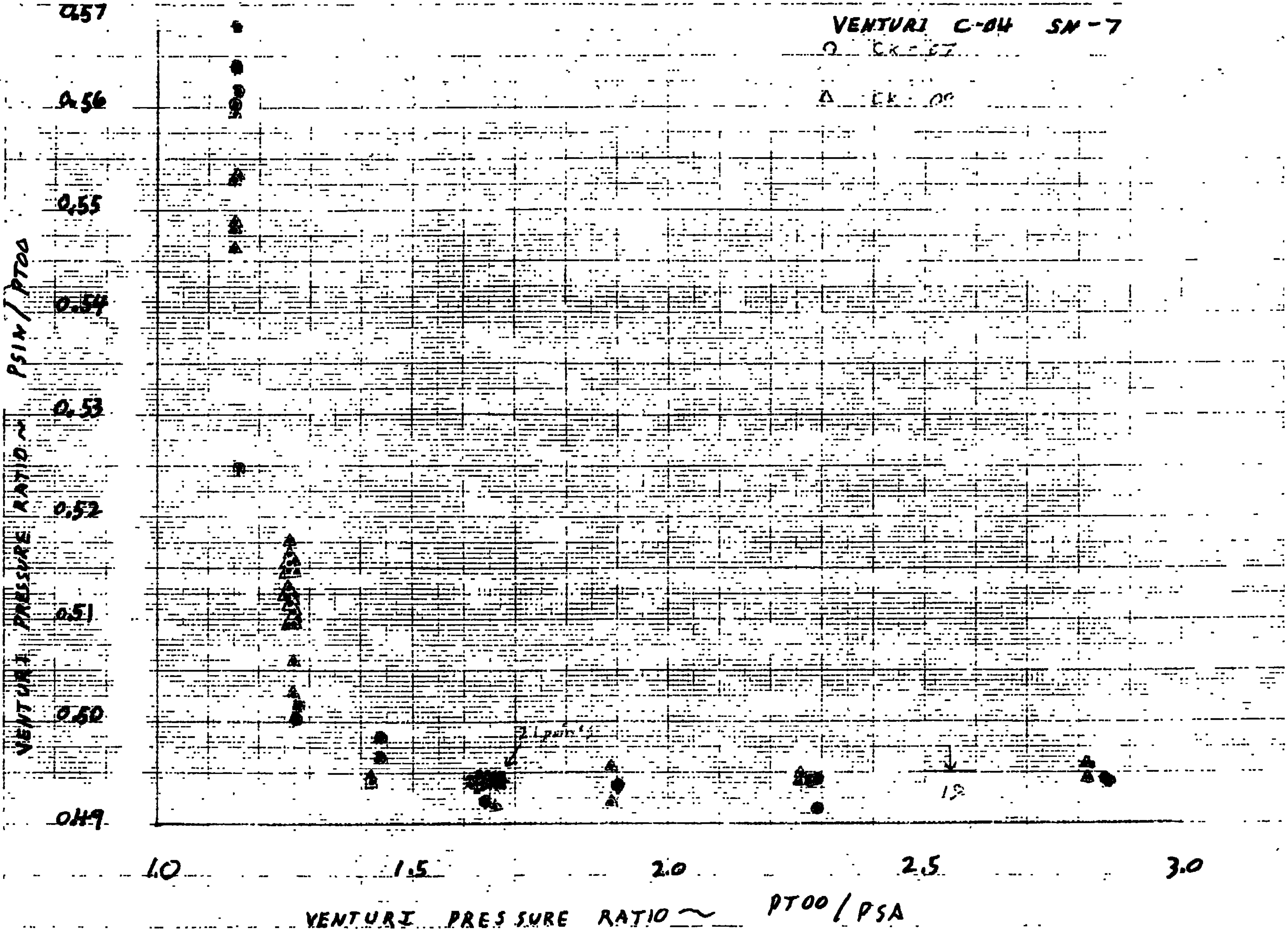


Figure 19 (Cont'd)

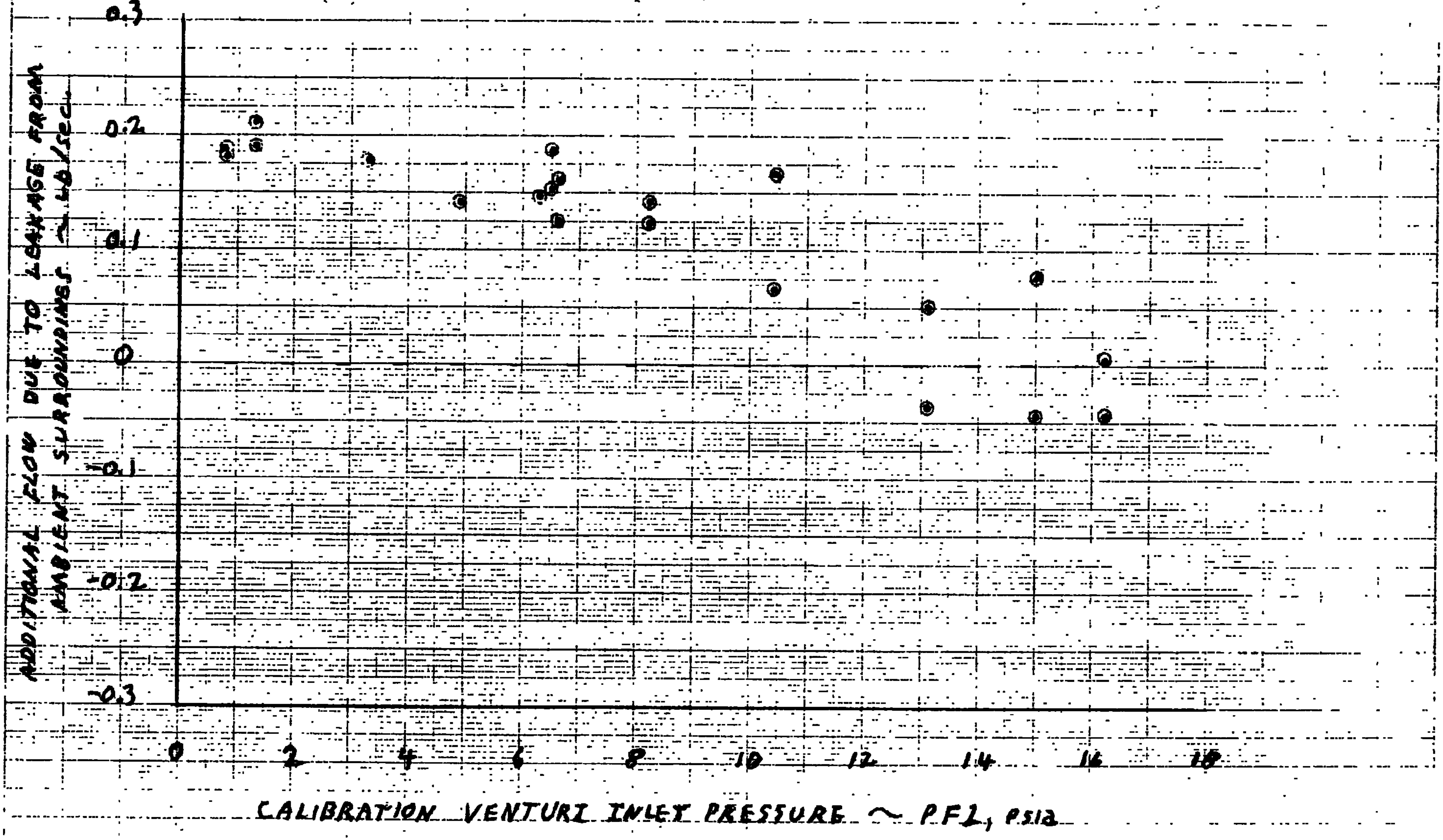


Figure 20. Inleakage Flow

TEST NUMBER	DATA POINTS	CONFIGURATION	FIXED VENTURIS OPEN	REMOTE VENTURIS OPEN	REFERENCE VENTURI
01	20	1	B 01 B 09 B 03 C 04 B 05 A 23 B 07	A 04 A 10 A 14 A 08 A 12 A 16 A 18	NONE
06	2	2	0	A 14	13"
	26	3	0	A 16	
	2	4	0	A 18	
07	16	5	B 01 C 04 B 03 A 23	A 12 A 14 A 08 A 10 A 16 A 18	35"
	8	6	B 01 C 04 B 03 A 23	A 16 A 12 A 14	
09	67	7	B 05 B 09 B 07 C 04	A 08 A 10 A 12 A 14 A 16 A 18	35"
10	14	8	B 01 B 09 B 03 C 04 B 05 A 23 B 07	A 02 A 08 A 12 A 16 A 20 A 04 A 10 A 14 A 18 A 22	NONE

Table 1. Venturi Configurations Test